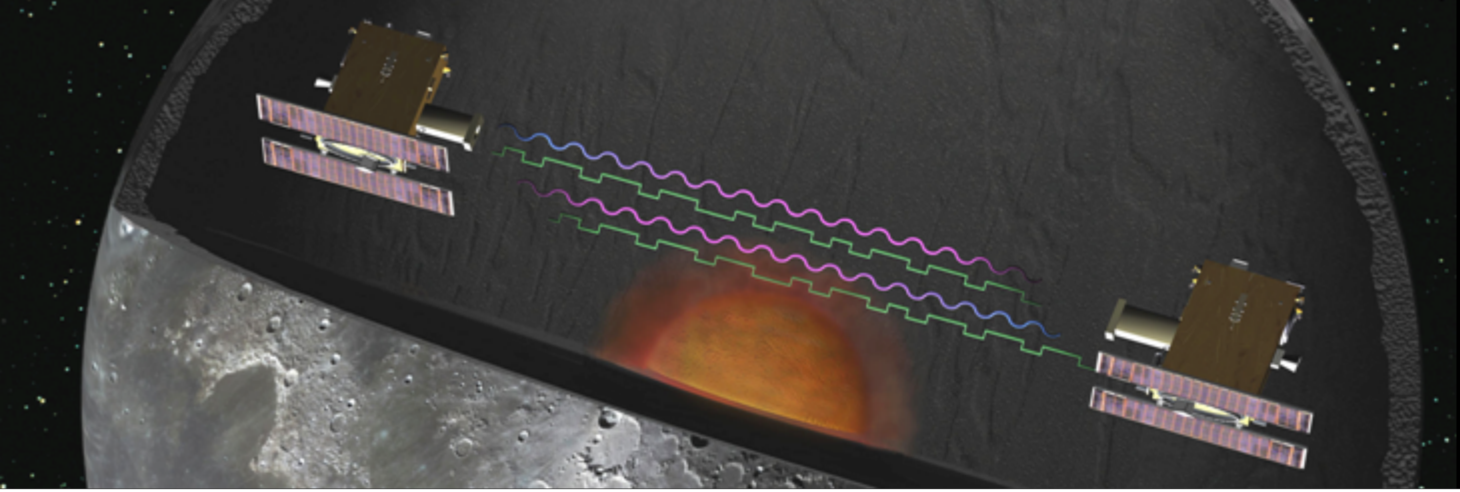


GRAIL

Gravity
Recovery
and
Interior
Laboratory

GRAIL Mission Overview

Mission Design and Navigation

Ralph B. Roncoli
representing the work of the GRAIL Mission Design and Navigation Teams

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

November 19, 2019
Johnson Space Center
Houston, Texas

Outline

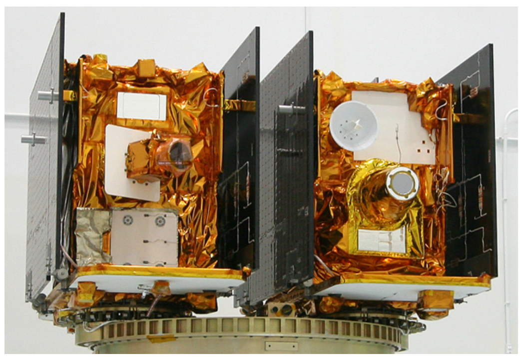
GRAIL
Discovery

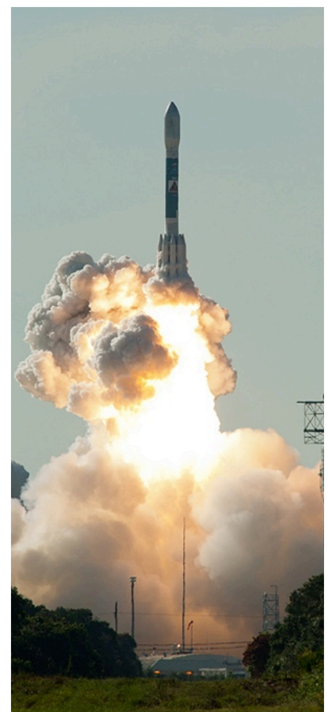
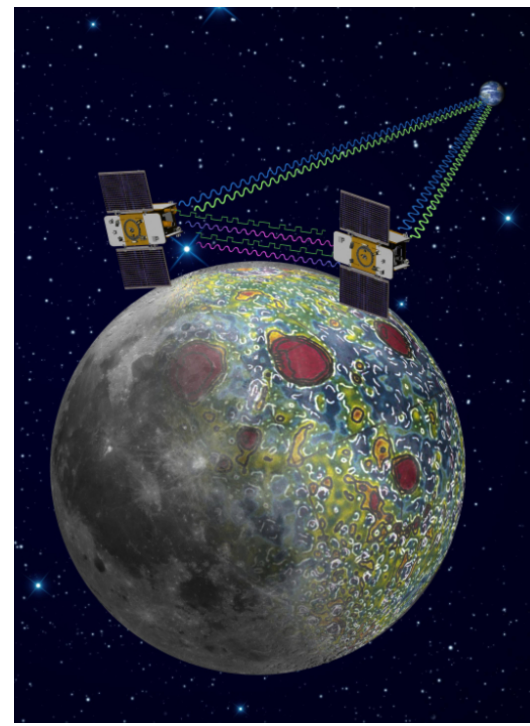
- Mission Overview
  - Mission Timeline / Mission Phases
  - Trajectory Design Challenges
    - Trans-Lunar Cruise Trajectory Design
  - Trajectory Design Challenges in the Extended Mission
    - Maintaining a Low-Altitude Orbit about the Moon
  - Trajectory Design Challenges in the End Game
    - Designing the Final Maneuvers
  - Mission and Navigation Operations
    - Maneuver and Orbit Determination Planning
  - Contingency Planning during the TLC Phase
    - TCM Planning
- Backup Slides
  - References
  - Trans-Lunar Cruise Trajectory Characteristics
  - Maneuver Strategy for the Transition to Science Formation Phase

GRAIL Mission

GRAIL
Discovery

- NASA Discovery Program
  - Gravity Recovery and Interior Laboratory (GRAIL) mission selected in December 2007
- Science Objectives
  - Determine the structure and interior of the Moon by precisely measuring the distance between two orbiters and tracking their position around the Moon
  - Map the global lunar gravity field to unprecedented accuracy and resolution
- Mission Management
  - JPL: Project Management / Payload
    - Includes Mission Design and Navigation
  - Lockheed Martin: Spacecraft Development
- Mission Operations
  - Jointly operated by JPL and LM
    - Benefited from extensive heritage from previous JPL/LM planetary missions and operational heritage from the GRACE mission

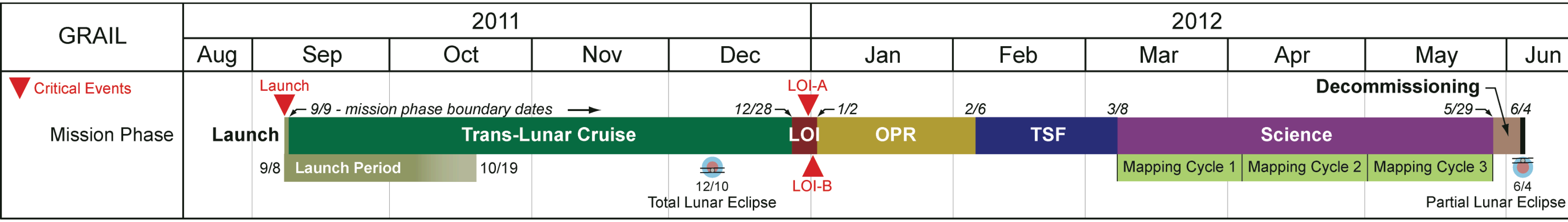



Mission Timeline / Mission Phases

GRAIL
Discovery

- Primary GRAIL Mission



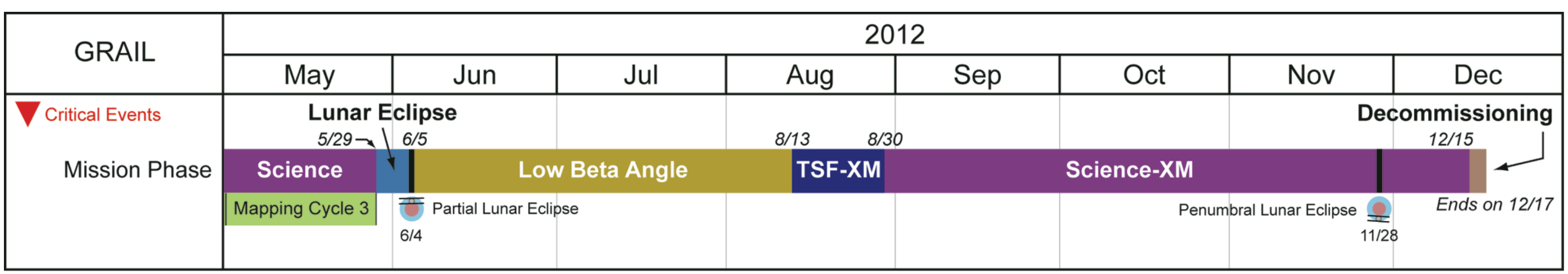
Mission Phases for Primary Mission

1) Launch Phase
2) Trans-Lunar Cruise (TLC) Phase
3) Lunar Orbit Insertion (LOI) Phase
4) Orbit Period Reduction (OPR) Phase
5) Transition to Science Formation (TSF) Phase
6) Science Phase
7) Decommissioning Phase

Mission Phases for Extended Mission

1) Lunar Eclipse (LEC) Phase
2) Low Beta Angle (LBA) Phase
3) Transition to Science Formation-XM (TSF-XM) Phase
4) Science-XM Phase
5) Decommissioning Phase

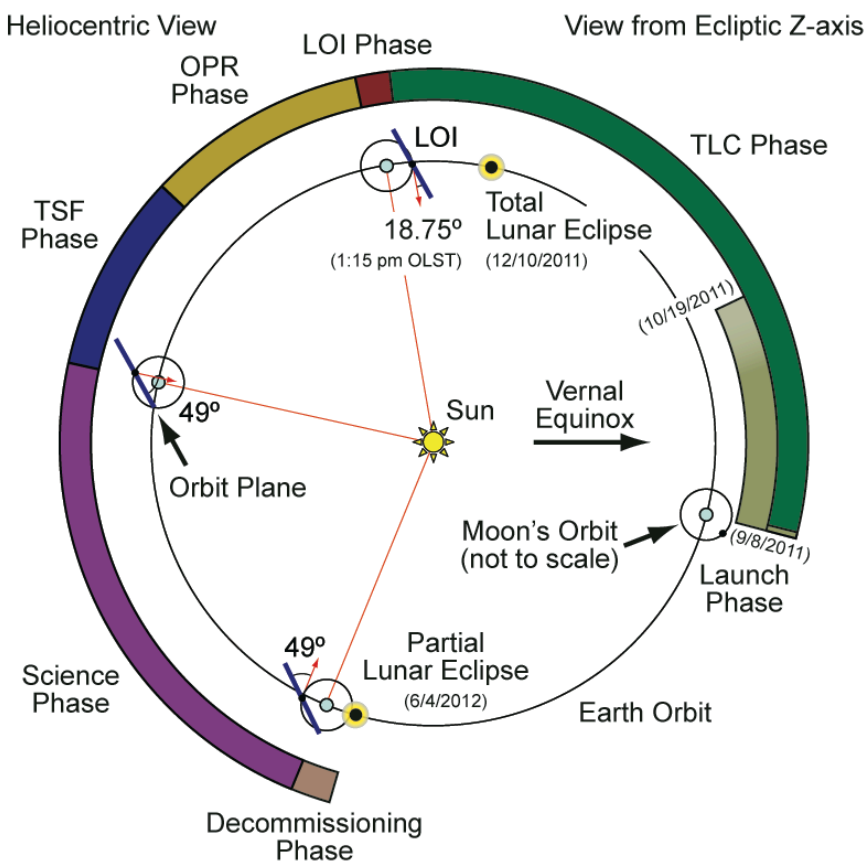
- Extended GRAIL Mission



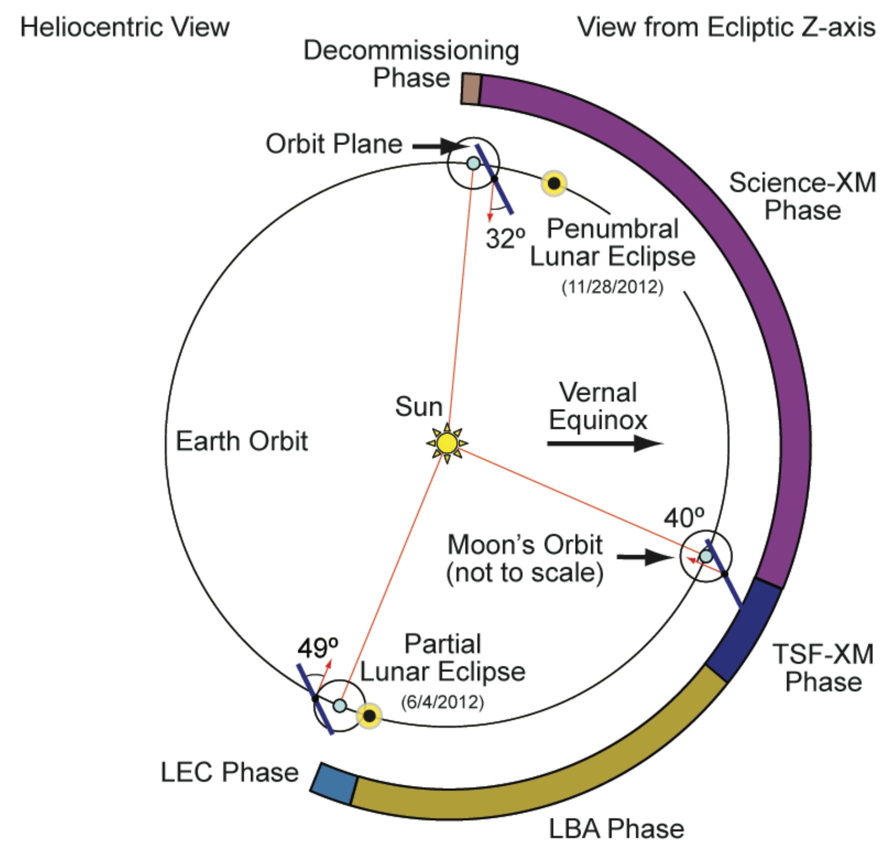
Mission Timeline / Mission Phases

GRAIL
Discovery

Primary GRAIL Mission



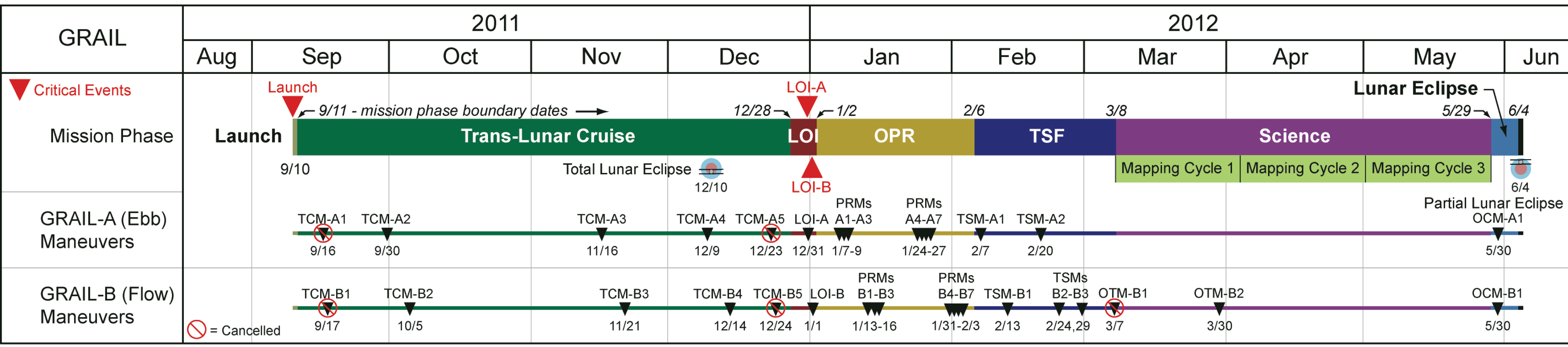
GRAIL Extended Mission



Primary Mission Maneuver Summary

GRAIL
Discovery

- Number of Maneuvers Performed: 28
  - GRAIL-A (Ebb): 13 (2 cancelled)
  - GRAIL-B (Flow): 15 (3 cancelled)



- Maneuver Terminology
  - TLC Phase: TCMs (Trajectory Correction Maneuvers)
  - LOI Phase: LOI (Lunar Orbit Insertion)
  - OPR Phase: PRMs (Period Reduction Maneuvers)
  - TSF Phase: TSMs (Transition to Science formation phase Maneuvers)
  - Science Phase: OTMs (Orbit Trim Maneuvers)

Primary Mission Overview – Transfer to the Moon

GRAIL
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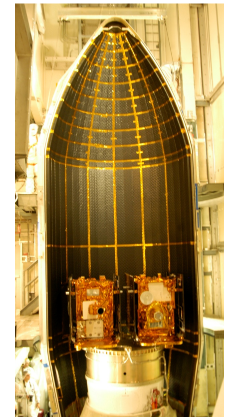
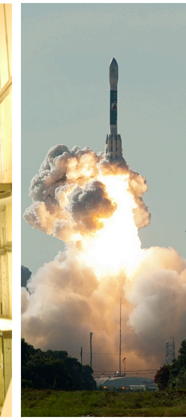
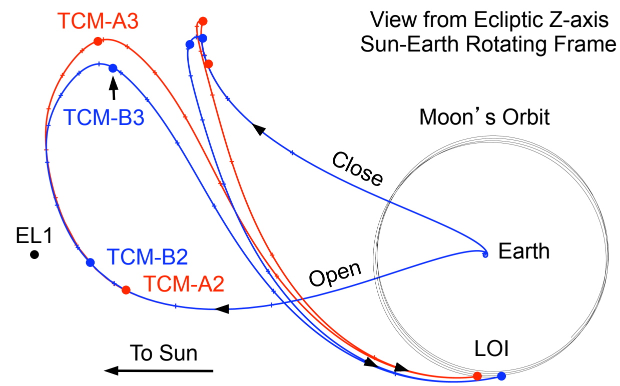
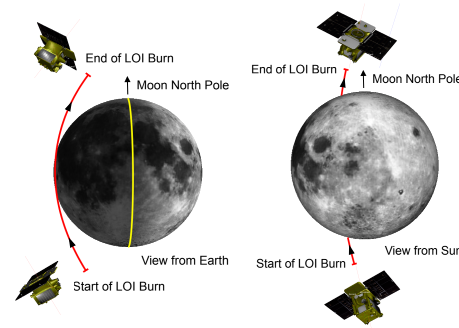
- Launch
  - Delta II 7920H-10C launch vehicle
  - Launch period: 08-Sep-2011 through 19-Oct-2011
    - Total of 42 launch days (original LP was 26 days long)
  - Constant arrival date (for all launch dates)
    - GRAIL-A: 31-Dec-2011
    - GRAIL-B: 01-Jan-2012 (Happy New Year!)
- Trans-Lunar Cruise
  - Low energy trajectory (3-4 month flight time to the Moon – 2 deterministic TCMs)
  - First NASA mission to baseline this type of lunar transfer trajectory (but not the first to consider it)
- Lunar Orbit Insertion
  - LOI maneuvers separated by ~ 25 hours
  - LOI maneuvers simultaneously visible from two Deep Space Network (DSN) tracking complexes
  - LOI burn duration ~ 38 min (ΔV ~ 192 m/s) resulting in a capture orbit period of 11.5 hours



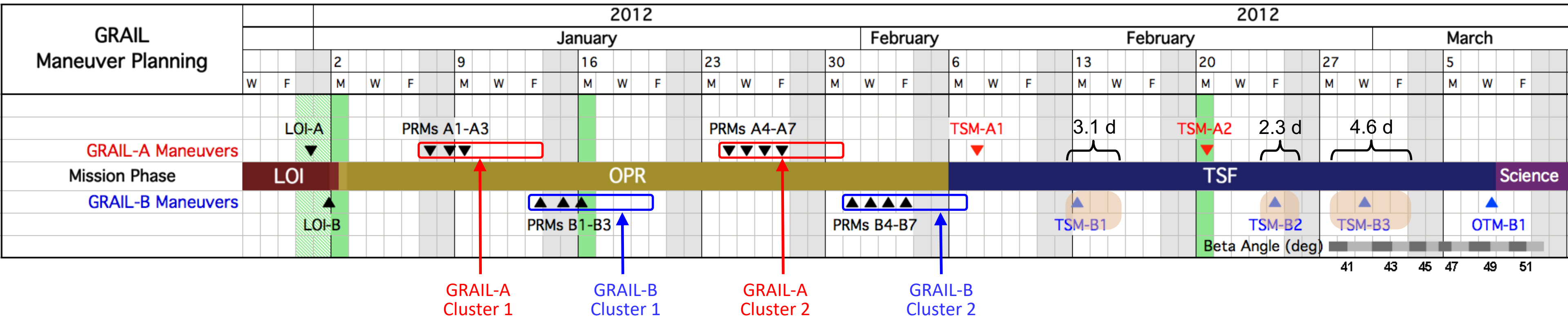




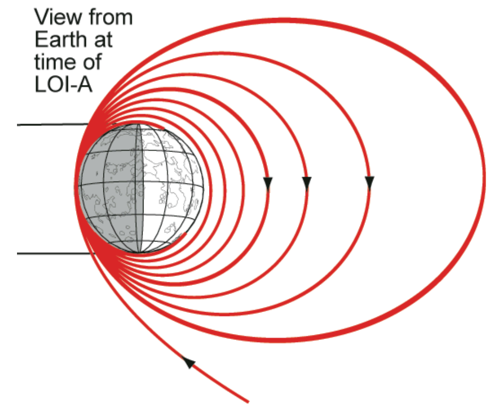


Primary Mission Overview – In Lunar Orbit

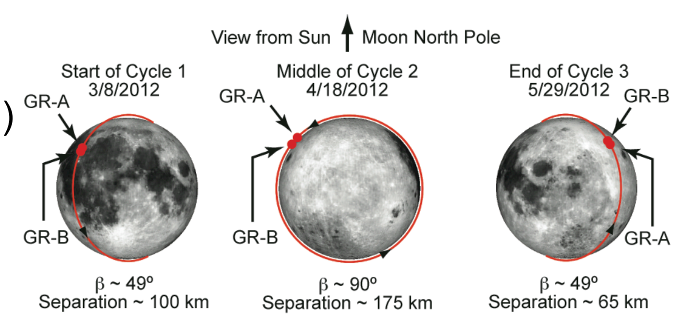
GRAIL
Discovery



- **Orbit Period Reduction**
  - Single maneuver design repeatedly performed to reduce period
  - Orbit period reduced to just under 2 hours in one month



- **Transition to Science Formation**
  - Five maneuvers used to establish the proper formation for the collection of gravity science data
  - First time that two spacecraft have been independently maneuvered into a precise orbit formation about another solar system body (other than the Earth)
- **Science**
  - Planned 82 day Science Phase (ended up being 89 days long)
  - Near-polar, near-circular science orbit with a mean altitude of 55 km
  - No orbit maintenance maneuvers required, only maneuvers to change separation distance
  - Orbiter separation distance varied between ~ 82 km and 217 km



Advantages of a Low-Energy Lunar Transfer

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Discovery

- General Benefits of a Low-Energy Transfer to the Moon
  - Reduction in spacecraft ΔV requirements as compared to the more common 3-6 day direct transfer trajectory (savings on the order of 120 m/s)
    - For GRAIL, this resulted in a lower cost mission option, allowing the use of a heritage spacecraft design and a smaller launch vehicle
  - Extended duration launch periods
    - Allows for launch period durations of more than 20 days
  - Fixed arrival date for all launch dates
    - Allows for the decoupling of trans-lunar cruise analyses from lunar orbit analyses

- GRAIL–Specific Benefits Using a Low-Energy Transfer to the Moon
  - Allowed time in cruise for spacecraft outgassing and stabilization of the Ultra Stable Oscillator (USO) prior to lunar orbit operations
  - Allowed time in cruise for system check-out and the ability to separate GRAIL-A and GRAIL-B TCMs
  - Allowed the ability to separate the GRAIL-A and GRAIL-B mission critical Lunar Orbit Insertion (LOI) maneuvers by one day

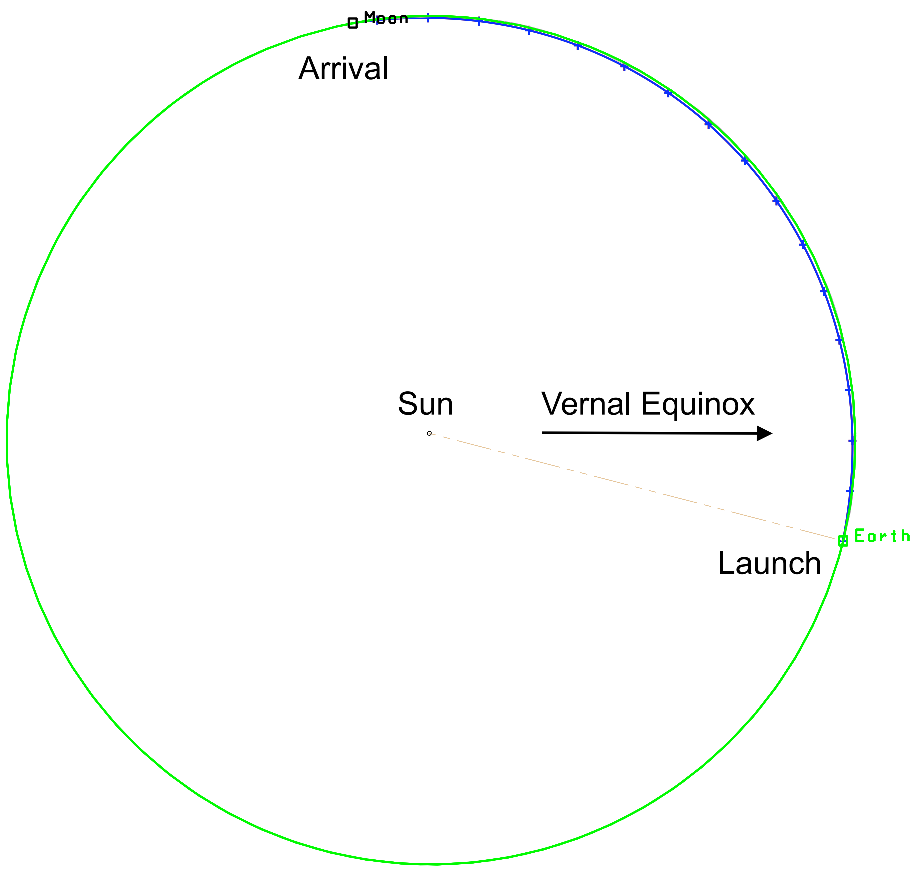
Low-Energy Trajectory Views

(Launch Period Open)

GRAIL
Discovery

Earth-Centered - Inertial View

Heliocentric View

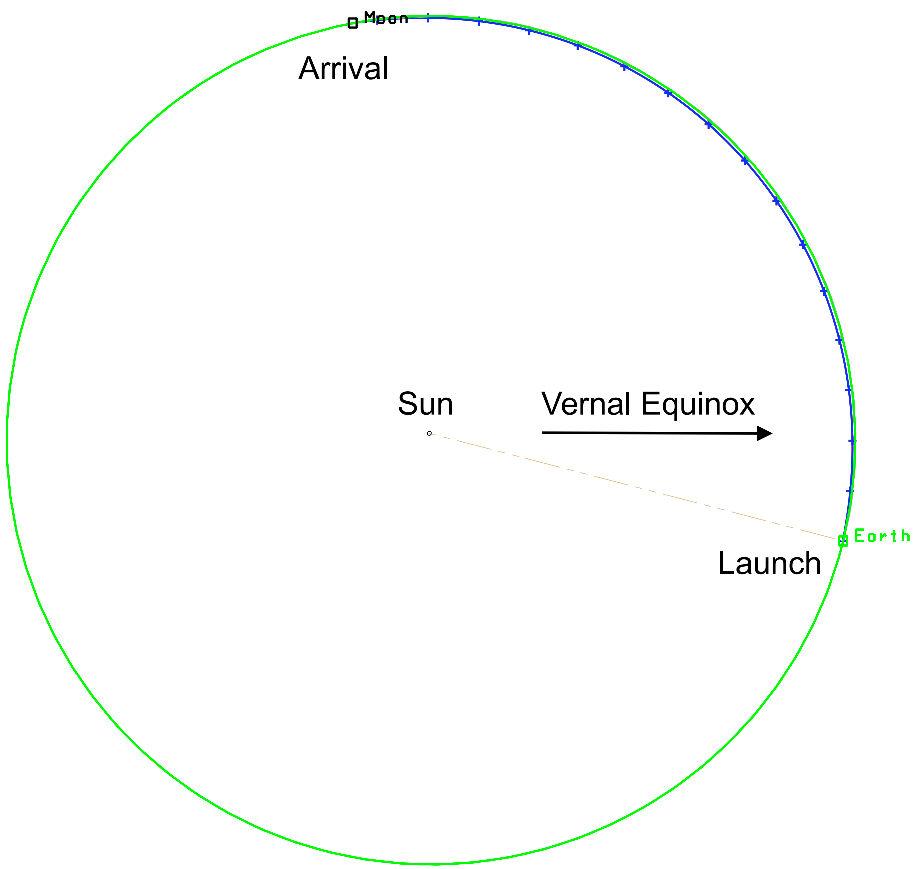


Earth-Centered - Sun-Earth Rotating View

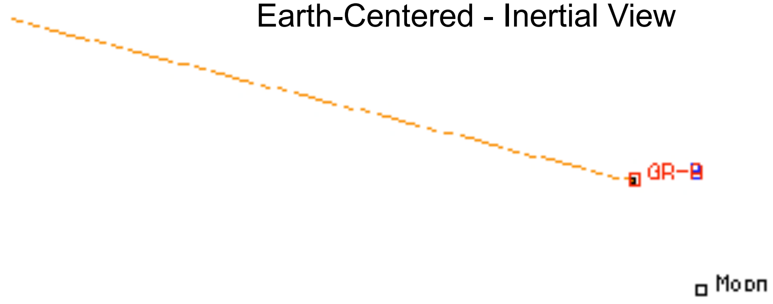
Low-Energy Trajectory Views
(Launch Period Open)

GRAIL
Discovery

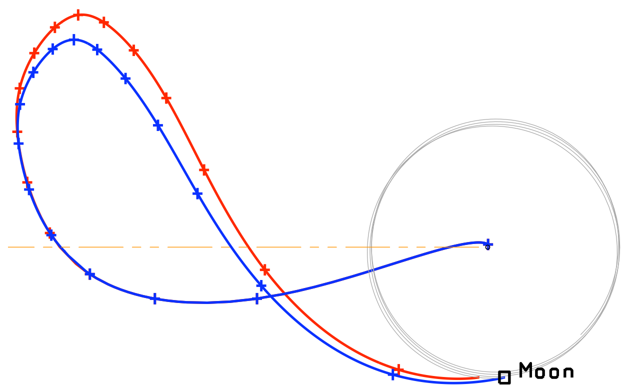
Heliocentric View



Earth-Centered - Inertial View



Earth-Centered - Sun-Earth Rotating View



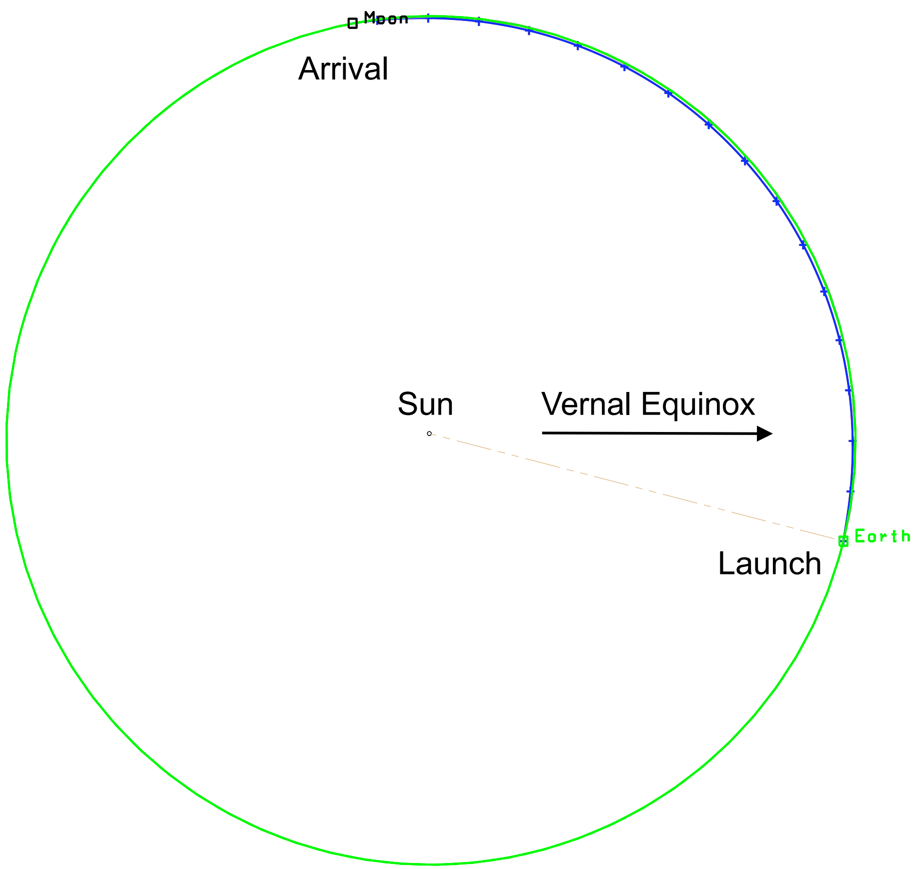
Low-Energy Trajectory Views

(Launch Period Open)

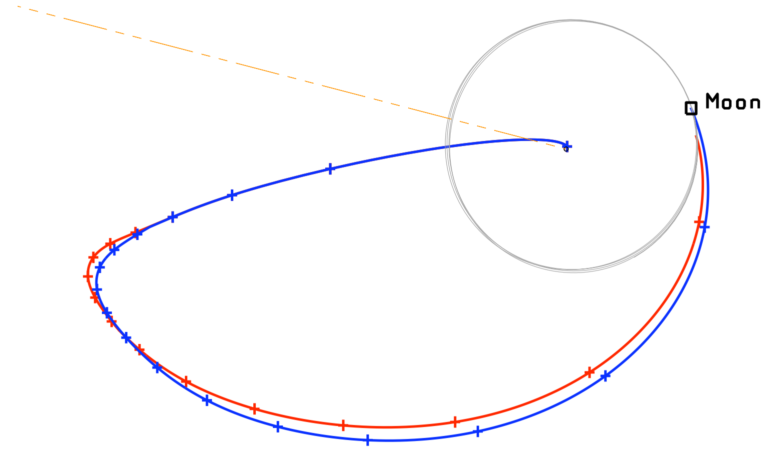
GRAIL

Discovery

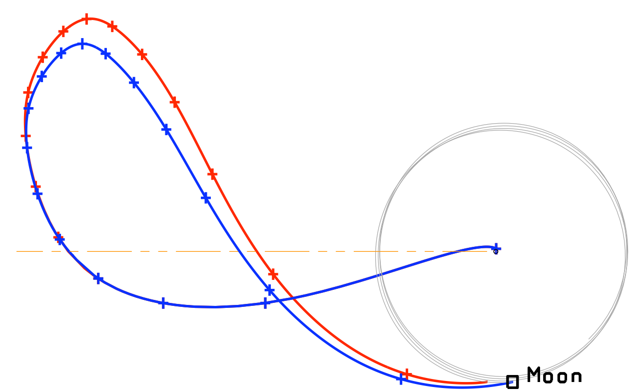
Heliocentric View



Earth-Centered - Inertial View



Earth-Centered - Sun-Earth Rotating View



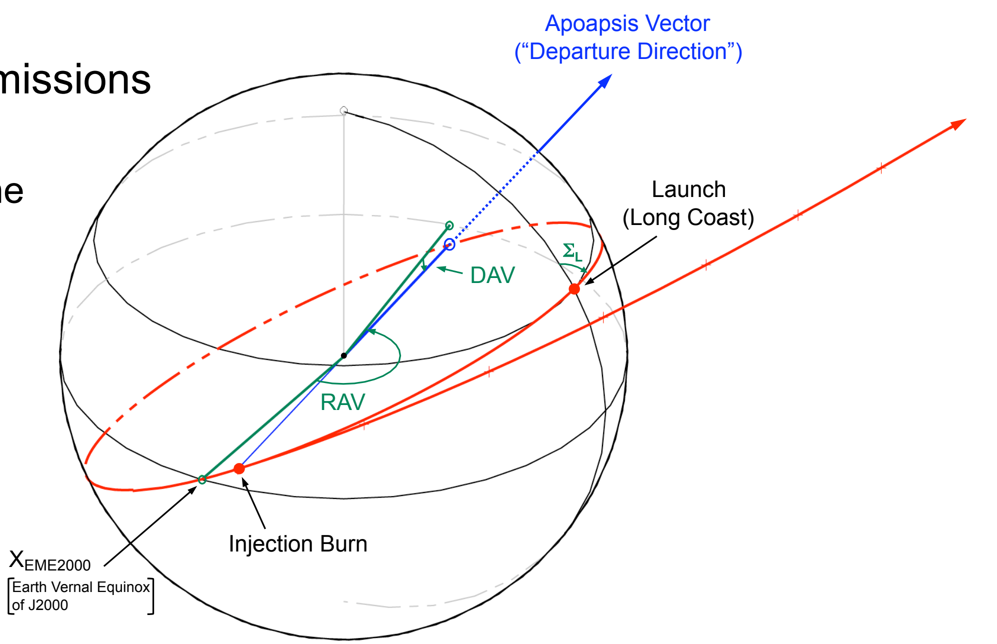
Trans-Lunar Cruise Trajectory Design

- General Characteristics of the TLC Trajectory
  - Launch trajectory along a stable manifold to a Lissajous orbit about the Sun-Earth Lagrange Point 1 (EL1)
  - However, instead of inserting into a Lissajous orbit – exit via an unstable manifold to the Moon
- Dual Spacecraft Launch on a Single Launch Vehicle
  - Two deterministic TCMs
    - TCM-2: Arrival time (LOI) separation
    - TCM-3: Manifold insertion
  - Three statistical TCMs
    - TCM-1: Correct launch vehicle injection errors
    - TCMs 4 and 5: Correct orbit determination errors and maneuver execution errors

Boundary Conditions

GRAIL
Discovery

- LOI Targets at the Moon
  - Arrival time, capture orbit period, periapsis altitude, orbit inclination, orbit node, approach direction (over the lunar south pole), latitude of periapsis – ALL FIXED
  - Only free variable is the instantaneous LOI ΔV magnitude (constrained to be in-plane)
- Injection (Launch) Targets at Earth
  - Traditional targets for interplanetary missions
    - Departure energy (C_3) (positive)
    - Declination and Right Ascension of the departure asymptote (DLA and RLA)
  - Low-energy trajectory does not have a “departure asymptote” since $C_3 < 0$
  - Analogous set of targets for GRAIL
    - Departure energy (C_3) (negative)
    - Declination and Right Ascension of the apoapsis vector (used to represent the “departure direction”) (DAV and RAV)
    - First time that this approach has been used by any mission



GRAIL Launch Targets
C_3 (twice the injection energy per unit mass, km^2/s^2)
DAV (declination of the injection orbit apoapsis vector, deg, EME2000)
RAV (right ascension of the injection orbit apoapsis vector, deg, EME2000)

  - Position and injection time determined by launch site and parking orbit

Trajectory Optimization

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- Theoretical Solution
  - Differentially correct two segments
    - A stable manifold to an EL1 Lissajous orbit from launch, and
    - An unstable manifold from the EL1 Lissajous orbit to the Moon

- Practical Solution
  - Search on the LOI ΔV magnitude until the backward propagated trajectory reaches the Earth approximately at the launch time
    - The backward propagated trajectory is a good estimate of the differentially-corrected segments except that the launch conditions are not met
  - Search on a launch trajectory that inserts into the backward propagated manifold and minimizes the total TLC ΔV (with TCMs at specified times)

Illustration of TLC Trajectory Design Process

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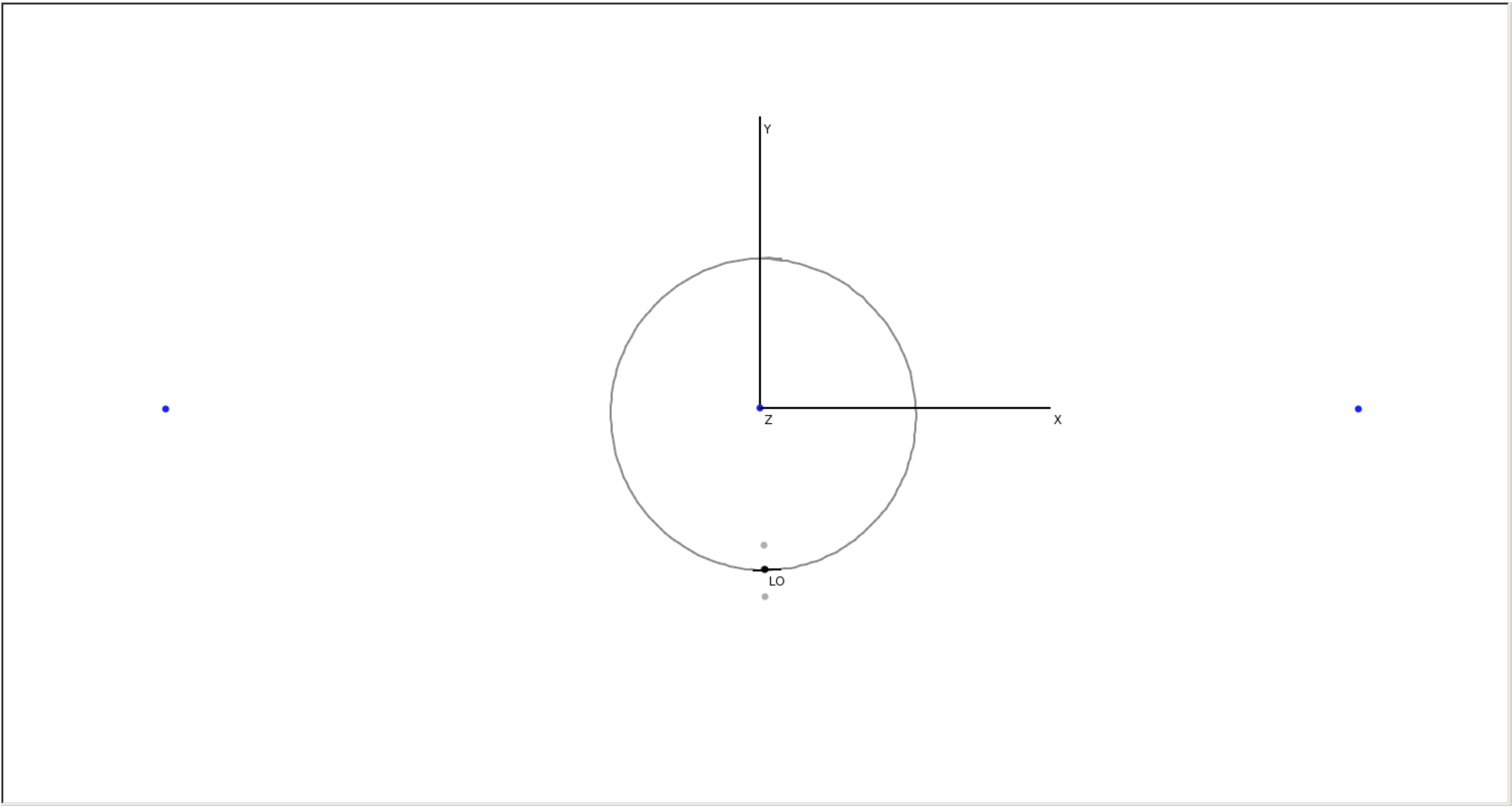
Discovery



Visualization of TLC Trajectory

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Discovery

[Depiction of the Change in Two-Body Ellipse about the Earth due to the Sun and the Moon]

Launch Period Design

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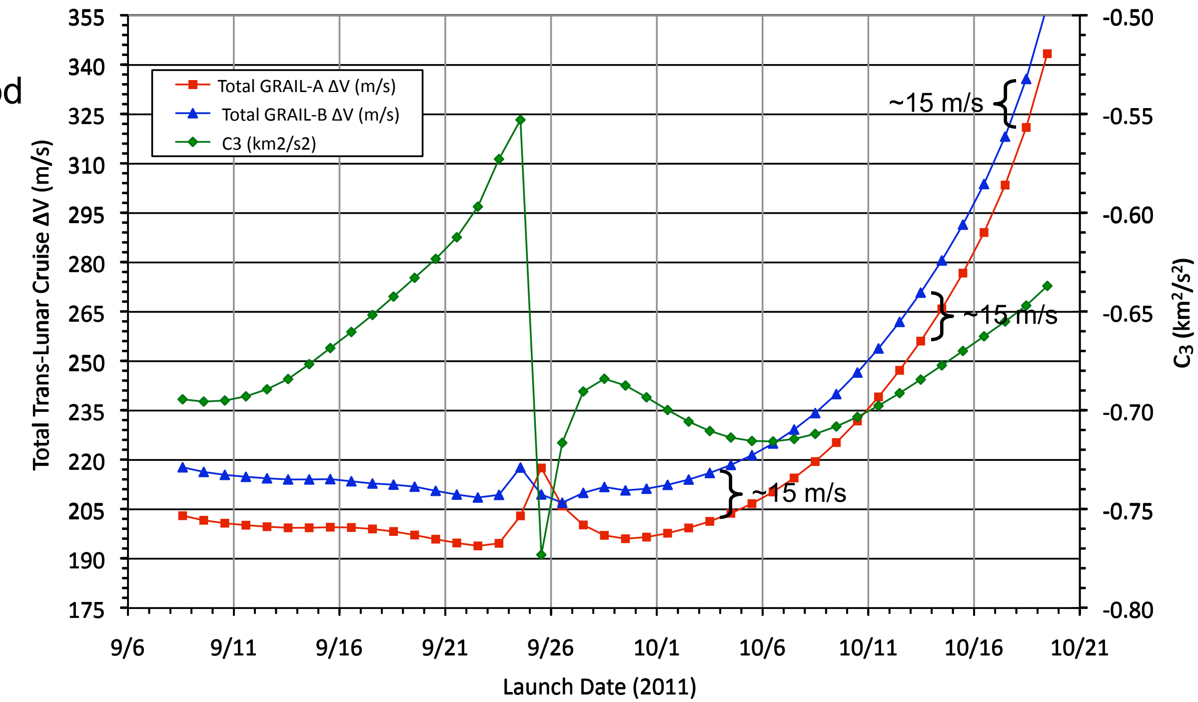
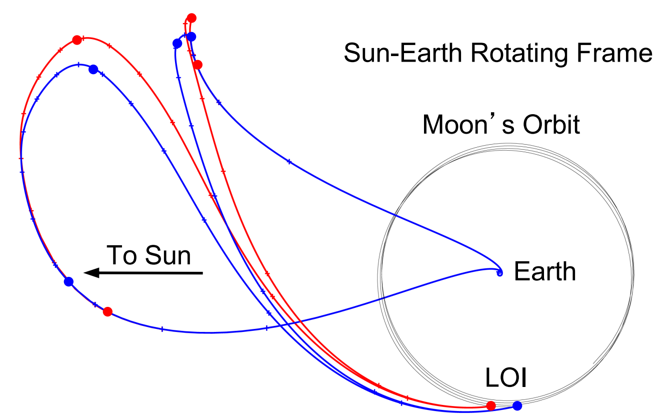
Discovery

- Baseline Launch Period
  - Minimize ΔV across launch period
  - Originally launch period was 26 days
- Balance GR-A and GR-B ΔVs
  - Weight the GR-A and GR-B ΔVs such that the difference in ΔVs is the same from day to day
    - Attempt to ensure that the end-of-mission ΔV margin is the same for GR-A and GR-B



- Extended Launch Period
  - Constrained by
    - Available propellant
    - Compression of Trans-Lunar Cruise timeline (ability to “fit” all activities into a shortened TLC Phase)
  - Final launch period was 42 days long !

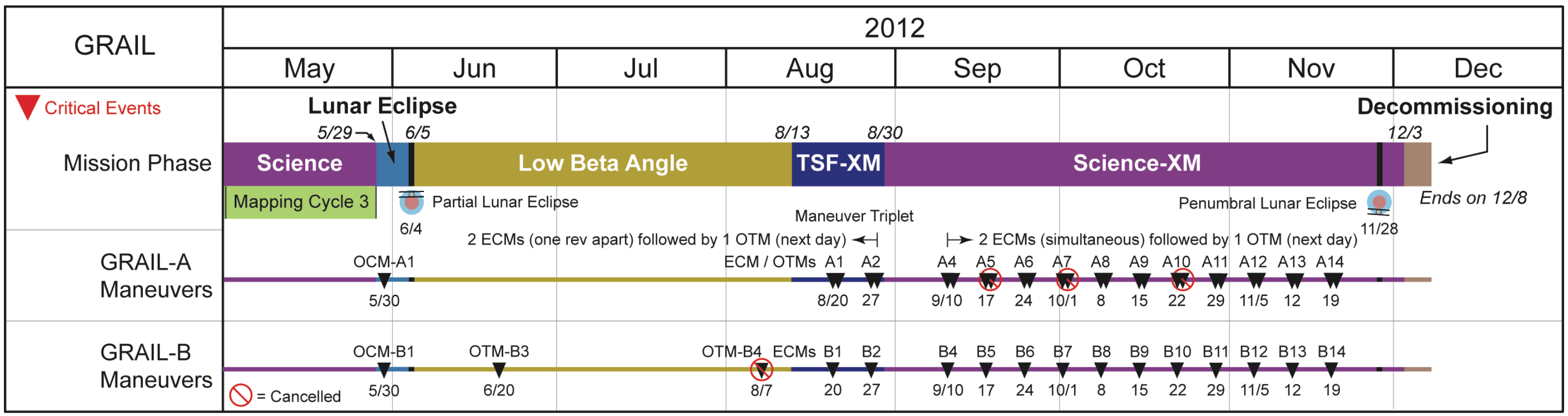


Extended Mission Maneuver Summary

(Excluding End Game)

GRAIL
Discovery

- Number of Maneuvers Performed: 39
  - GRAIL-A (Ebb): 24 (3 cancelled)
  - GRAIL-B (Flow): 15 (1 cancelled)

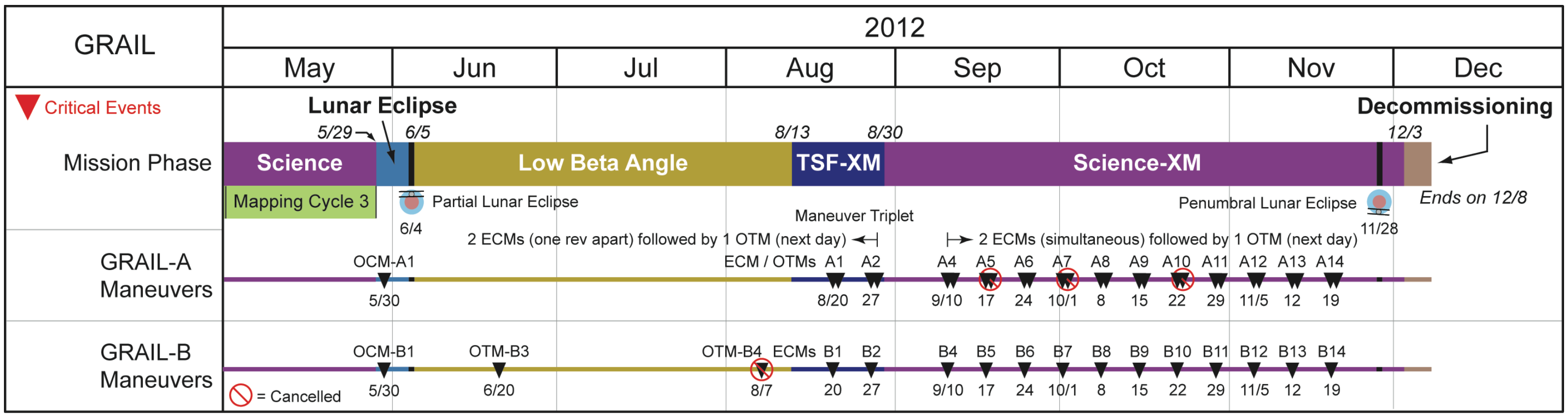


Before End Game was developed

- Maneuver Terminology
  - LEC Phase: OCMs (Orbit Circularization Maneuvers)
  - Multiple Phases: ECMs (Eccentricity Correction Maneuvers)
  - Multiple Phases: OTMs (Orbit Trim Maneuvers)

Extended Mission Overview

GRAIL
Discovery

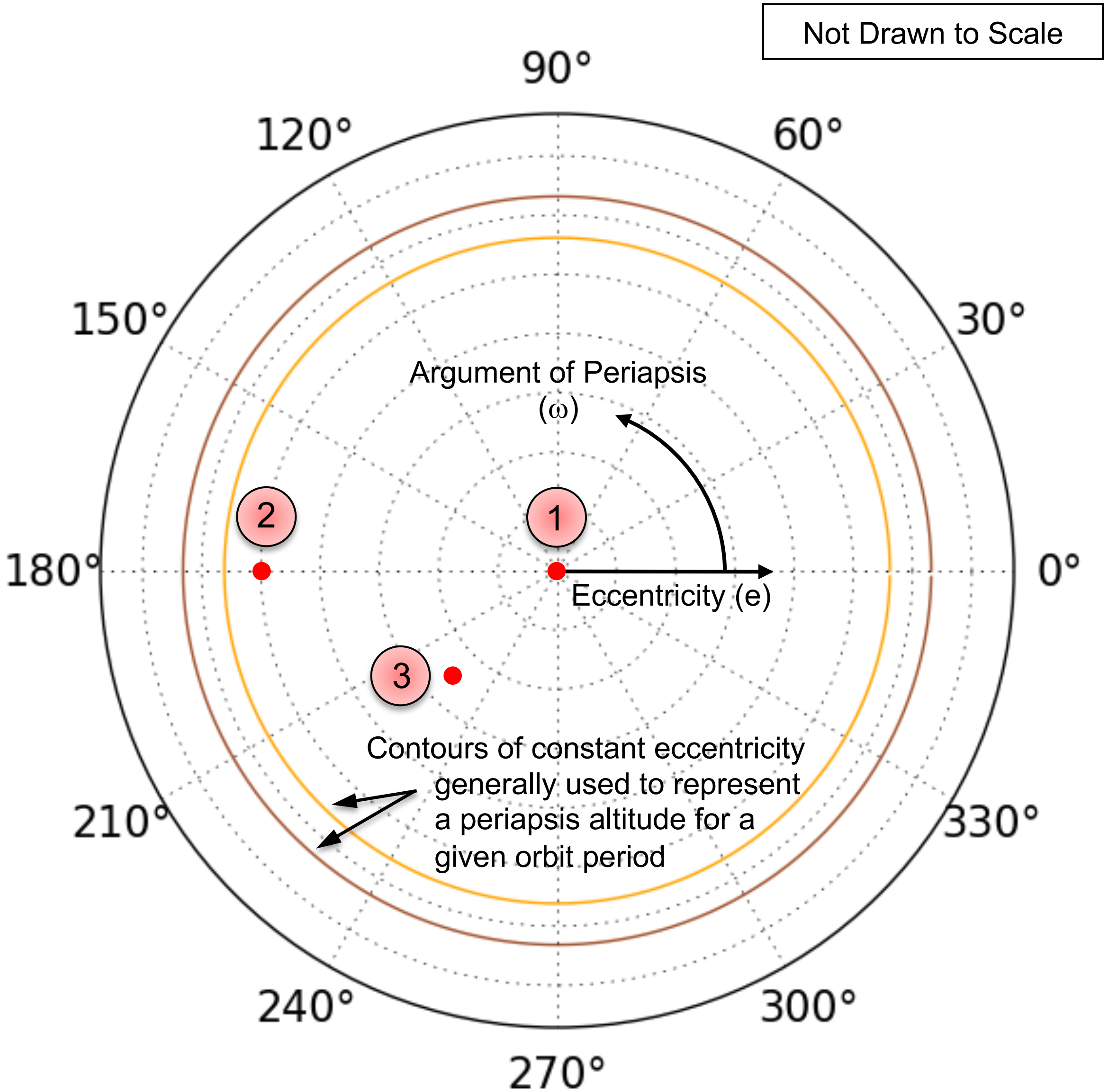


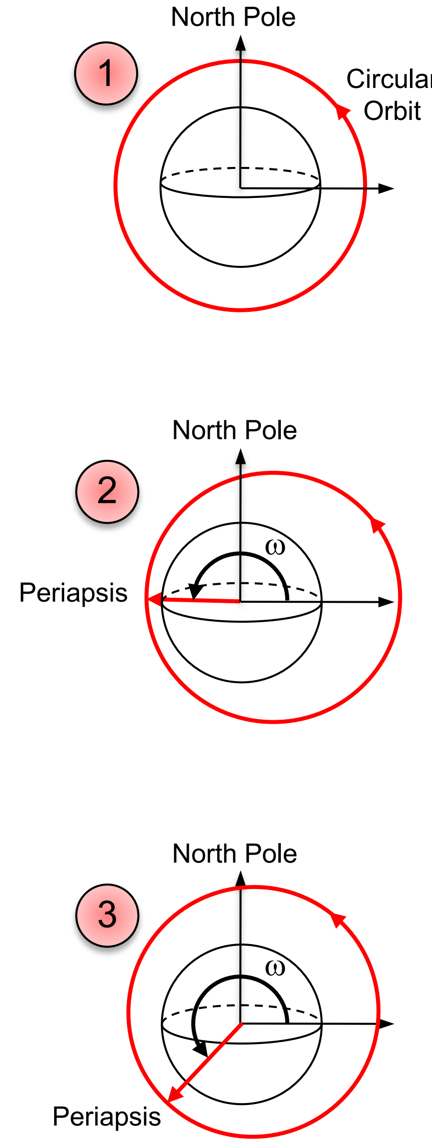
Before End Game was developed

- Lunar Eclipse
  - Avoid impacting the surface and prepare for passage through the partial lunar eclipse
- Low Beta Angle
  - No science possible – manage the separation rate between the two orbiters to achieve the desired separation distance in mid August
- Transition to Science Formation – Extended Mission
  - Lower the orbit altitude to the new science orbit and establish the initial conditions for the next phase
- Science – Extended Mission
  - Perform "standard triplet of maneuvers" every week for 14 weeks (except Labor Day!) in order to
    1. Manage the evolution of the eccentricity and argument of periapsis (i.e. the eccentricity vector)
    2. Control the separation distance by adjusting the separation rate prior to the next set of maneuvers
  - Achieve a mean orbit altitude of 23.5 km with a targeted separation distance of 60 km
- Decommissioning
  - "Disposing" of the spacecraft in a scientifically interesting way was TBD for much of the XM

Introduction to Eccentricity Vector Space

GRAIL Discovery





e-ω Plot for Primary Mission Science Phase

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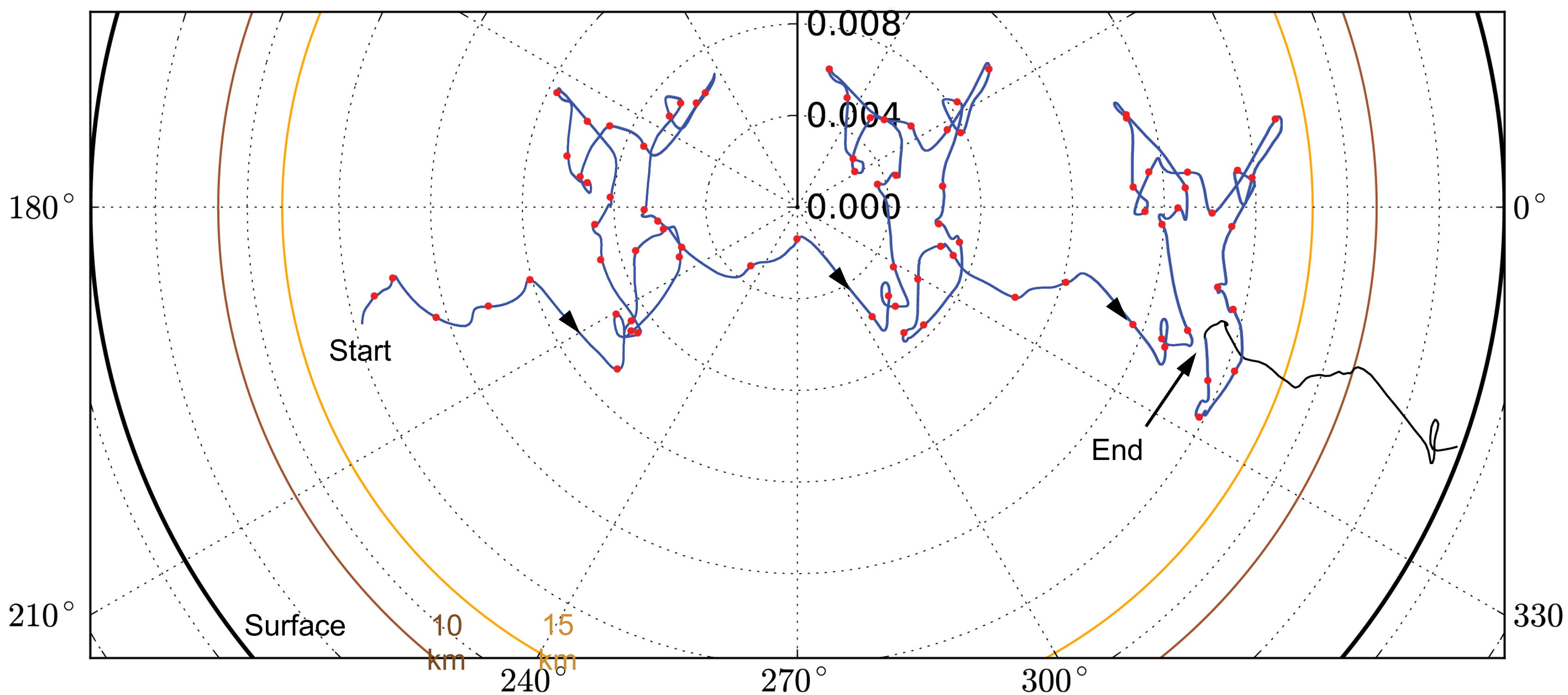
Discovery

- Primary Mission Science Phase = 82 days
  - March 8th to May 29th, 2012
  - 3 lunar sidereal months (3 x 27.3 days) = 3 Mapping Cycles
- Mean orbit altitude = 55 km
  - No orbit maintenance maneuvers – orbit evolves from elliptical, to near-circular, back to elliptical



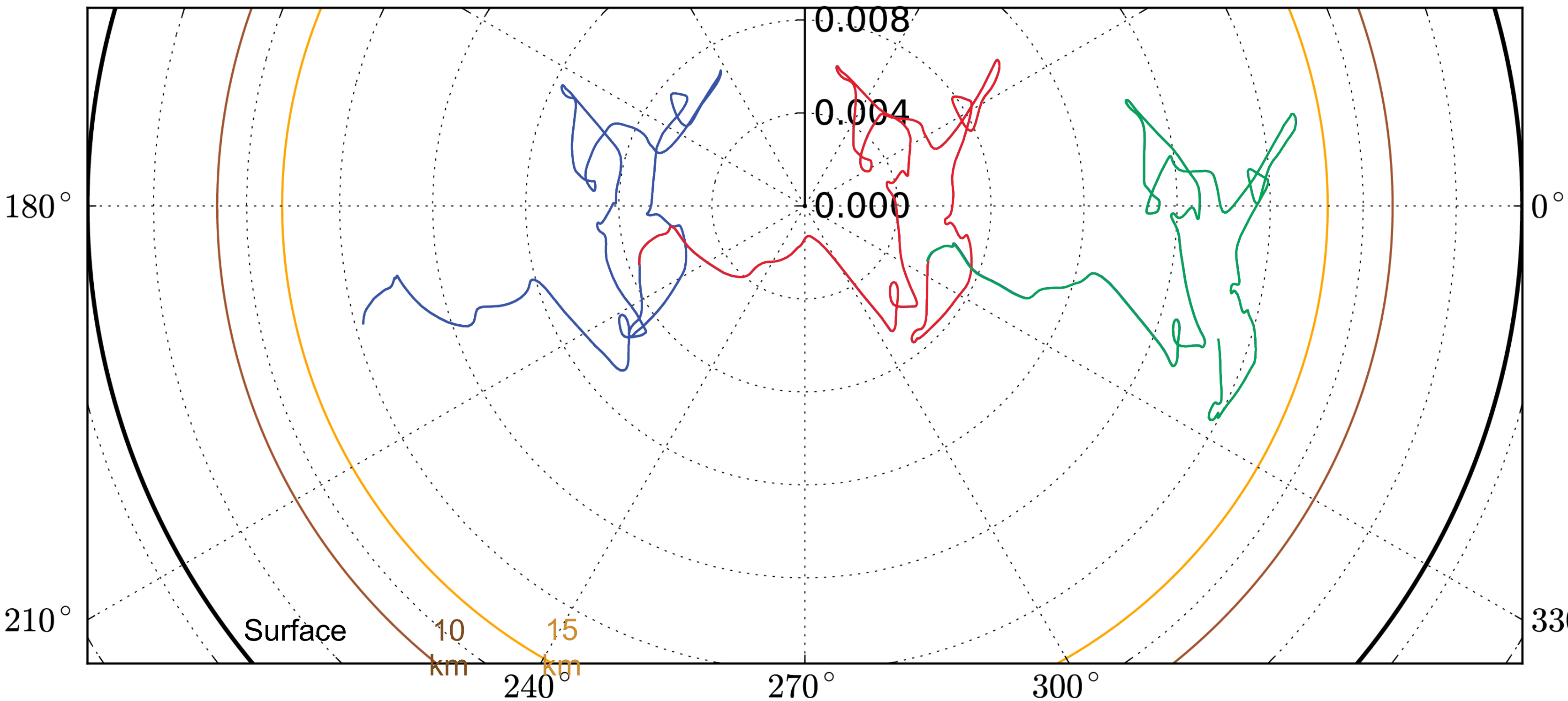
Lunar gravity field = LP150Q (150x150)

Managing the e-ω Evolution

GRAIL Discovery

- Adding Maneuvers
  - To minimize the maximum altitude variation and potentially lower the mean orbit altitude

- Consider the case of performing a maneuver after each Mapping Cycle (27.3 days)
- Centering the e-ω evolution minimizes the maximum altitude variation



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GRAIL
Discovery

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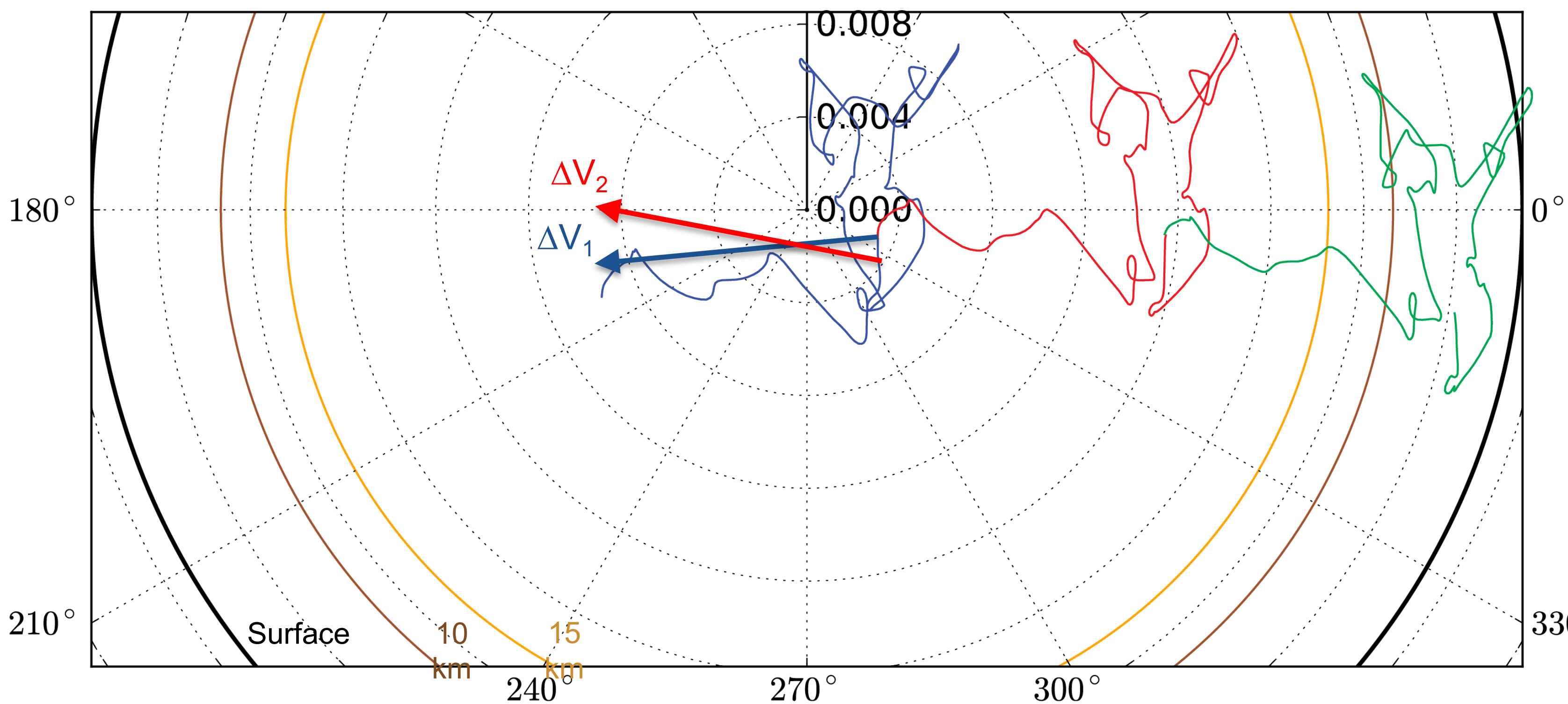

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Managing the e-ω Evolution

GRAIL
Discovery

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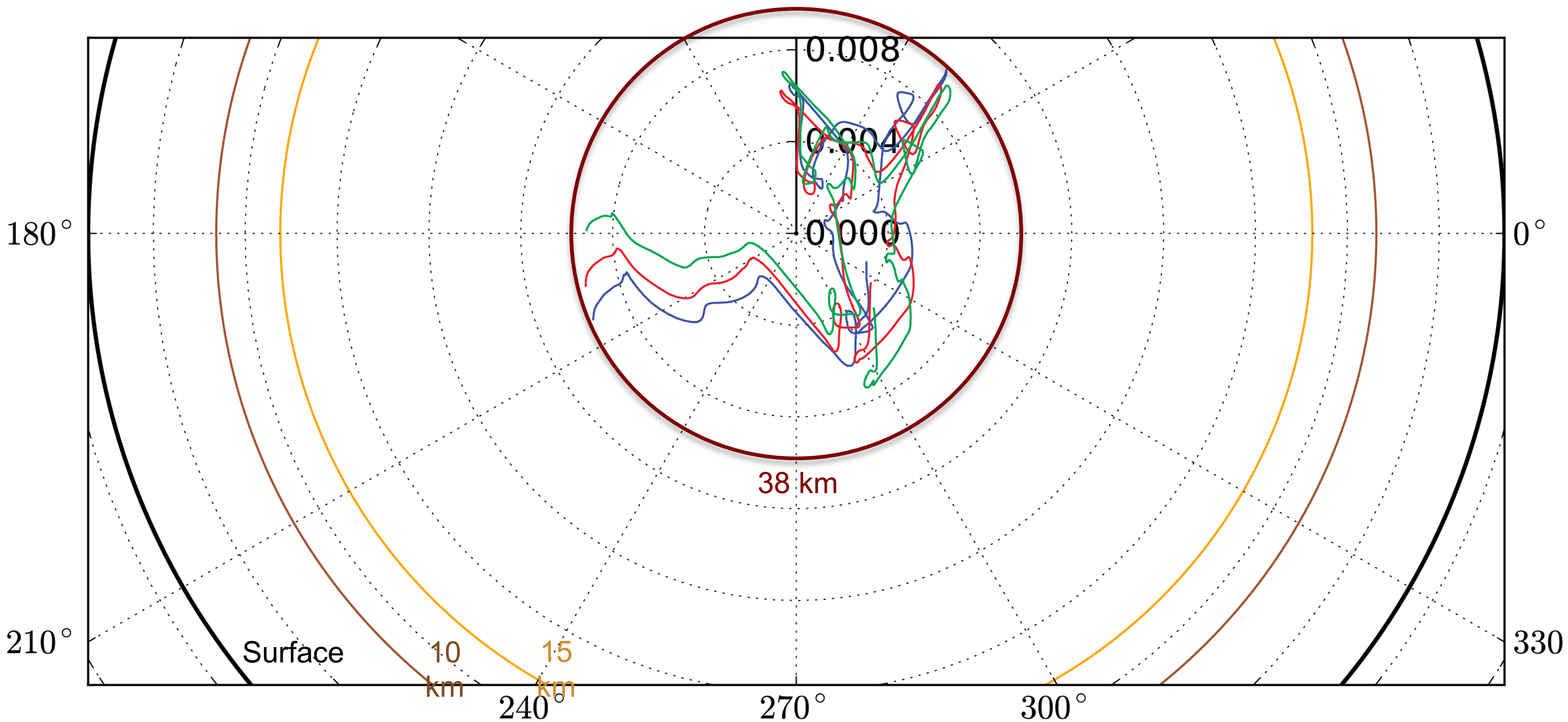


Lunar gravity field = LP150Q (150x150)

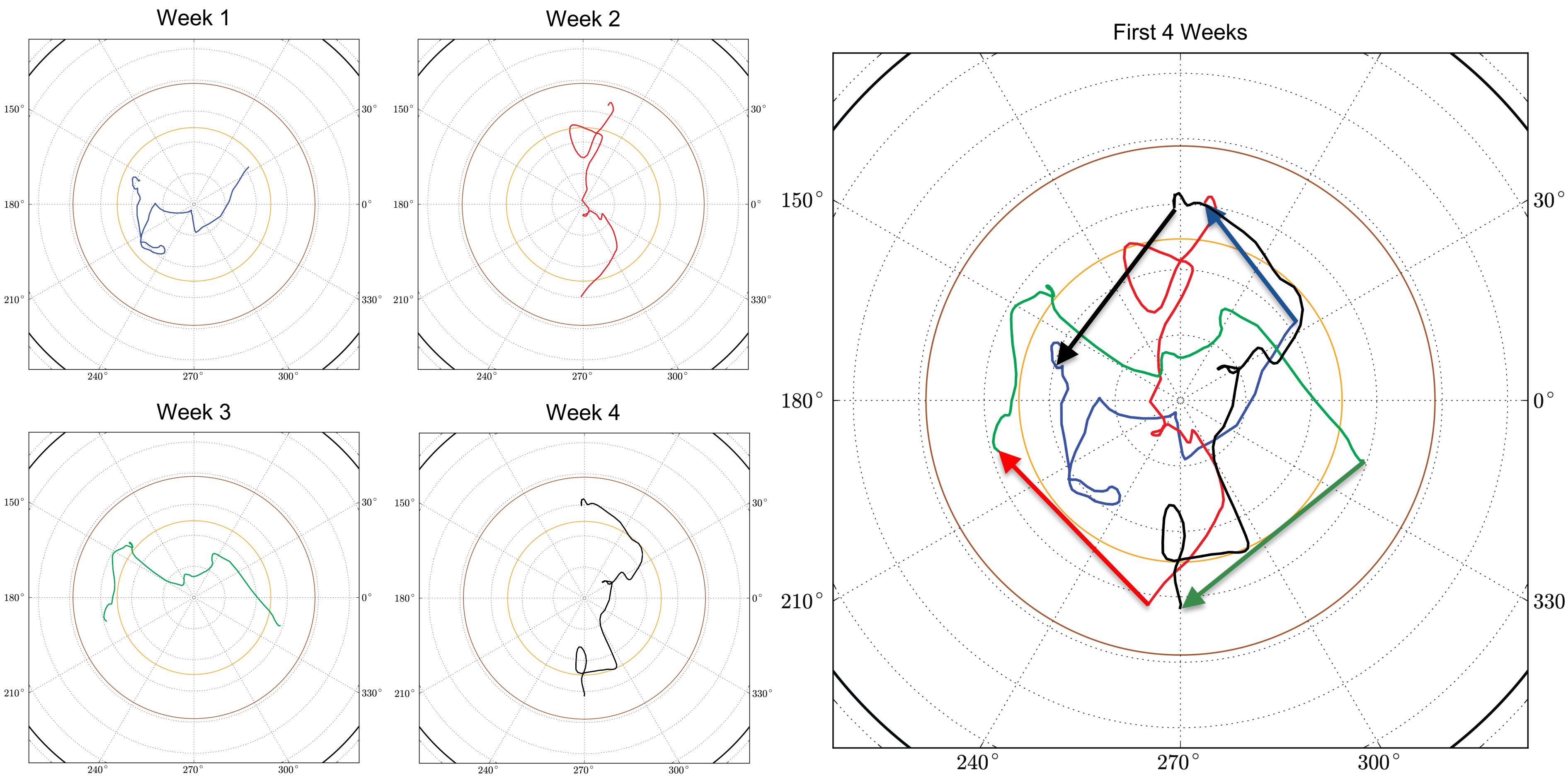
Extended Mission Science Orbit Design

- Principal Design Factors
  - Science
    - Mean orbit altitude – as low as possible
    - Maximum altitude variation (max apoapsis to min periapsis) – as small as possible
  - Operations / Flight System
    - Frequency of “orbit reset maneuvers” (or ECMs – for Eccentricity Correction Maneuvers)
      - Don’t change existing operations processes (e.g. maneuver development templates)
    - Orbit lifetime – ensure a minimum orbit lifetime of at least 7 days in the case of a missed maneuver
    - ΔV requirements – smaller is better, but little need to save ΔV for future use
- Trade Space
  - Evaluated many different options, but focused primarily on operationally simple options with maneuvers performed
    - Once every 28 days
    - Once every 14 days
    - Once every 7 days
    - Evaluated different “days-of-the-week” for maneuvers --- it matters !

Making the 7-day Reset Option Work

GRAIL Discovery

- Centering the weekly e-ω segments – 1st month



- and repeat for 2 more months ...
- and then repeat again varying the ECM day-of-the-week, optimizing ΔV, and so on …

GRAIL Extended Mission Science Orbit

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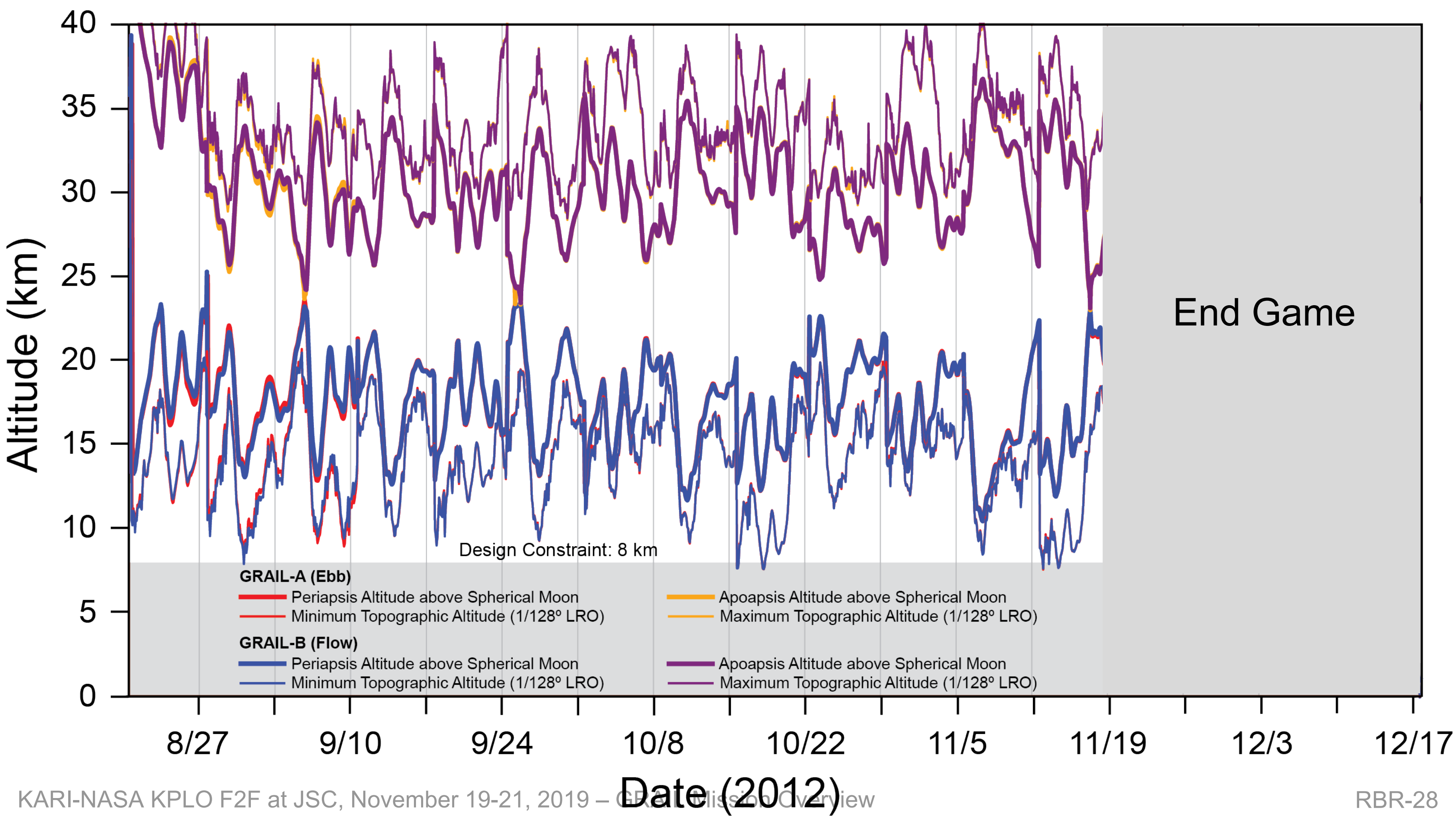
Discovery

- GRAIL-PM: Mean orbit altitude = 55.0 km
- GRAIL-XM: Mean orbit altitude = 23.5 km



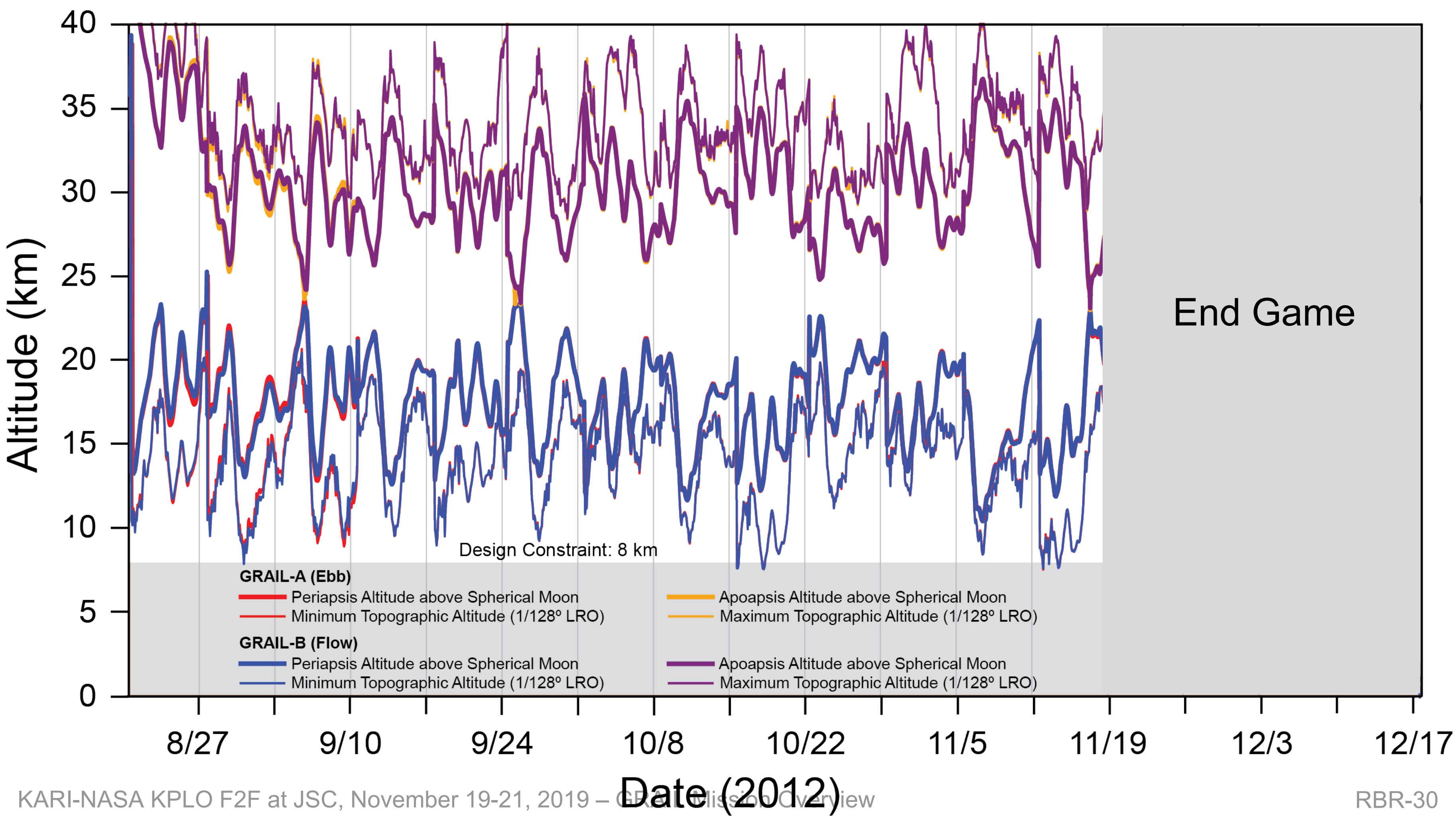
End Game Objectives

- Original End-of-Mission (as described in the proposal submitted to NASA in March 2012)
  - No specific End Game objectives were identified
  - Final maneuvers on were November 19th (no change in mean altitude from earlier maneuvers)
  - Orbit would evolve to an impact on or about December 7th
- What to do? How to get the most out of the mission?
  - Impact a crater wall? Collect more gravity science data?
- Conclusion (reached during the late summer / early fall of 2012)
  - Continue to collect gravity science data for as long as possible at lower and lower altitudes!
- Constraints on End Game Duration
  - Spacecraft
    - Power and Thermal – limits duration of science data collection
    - Available propellant – limits orbital lifetime
  - Site Impact Targeting
    - Minimize the potential of disturbing "Lunar Heritage Sites"

GRAIL Extended Mission Science Orbit

GRAIL
Discovery

- GRAIL-PM: Mean orbit altitude = 55.0 km
- GRAIL-XM: Mean orbit altitude = 23.5 km
- End Game: Mean orbit altitude = 23.5 km to 20.0 km to 11.5 km to 12.5 km



End Game Minimum and Maximum Altitudes

GRAIL
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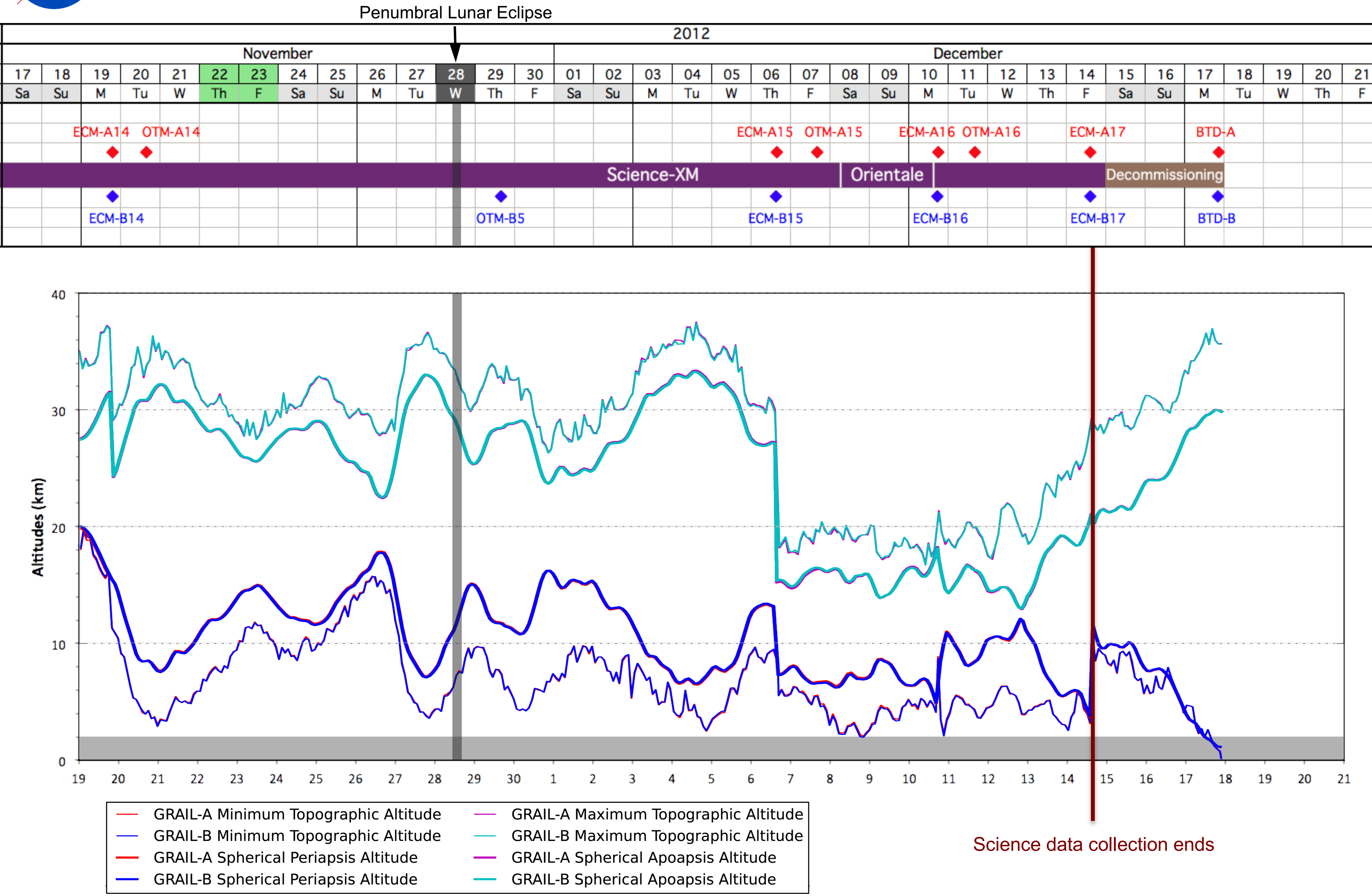

Extended Mission Maneuver Summary

(Including End Game)

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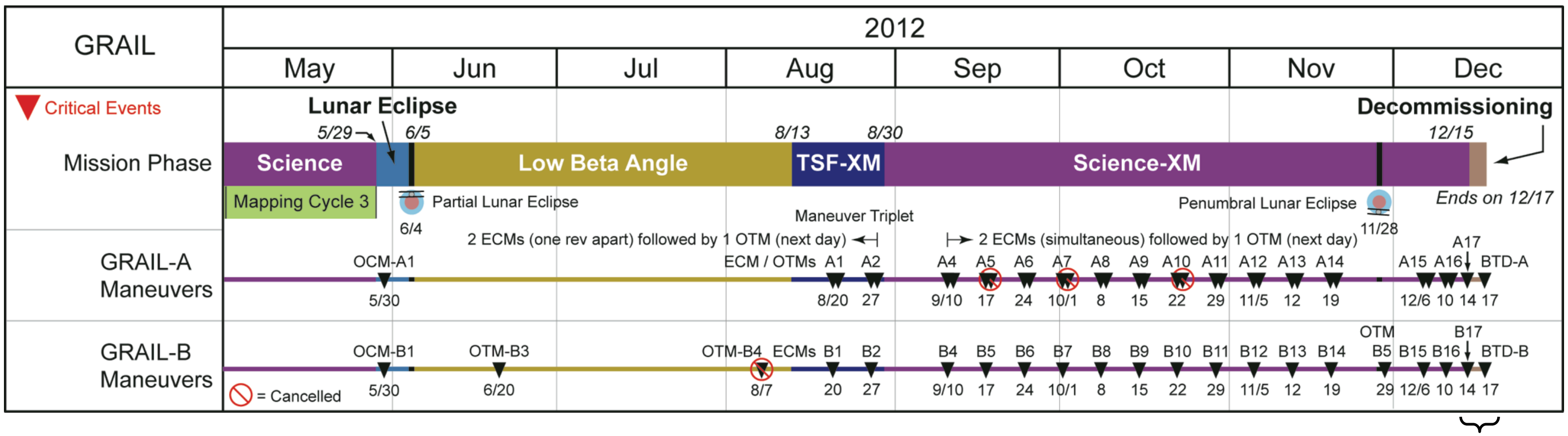
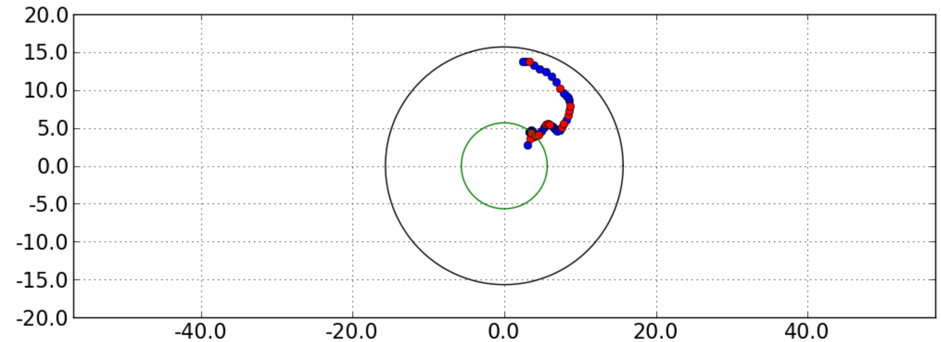
- Number of Maneuvers Performed: 50
  - GRAIL-A (Ebb): 30 (3 cancelled)
  - GRAIL-B (Flow): 20 (1 cancelled)

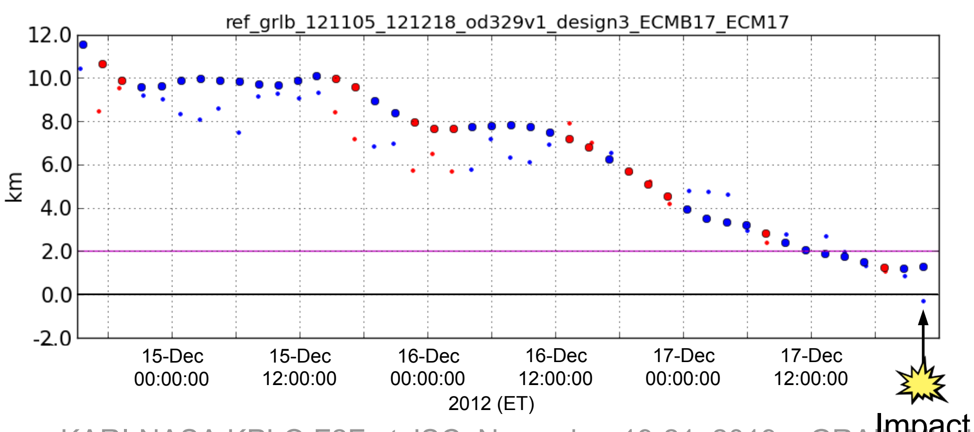


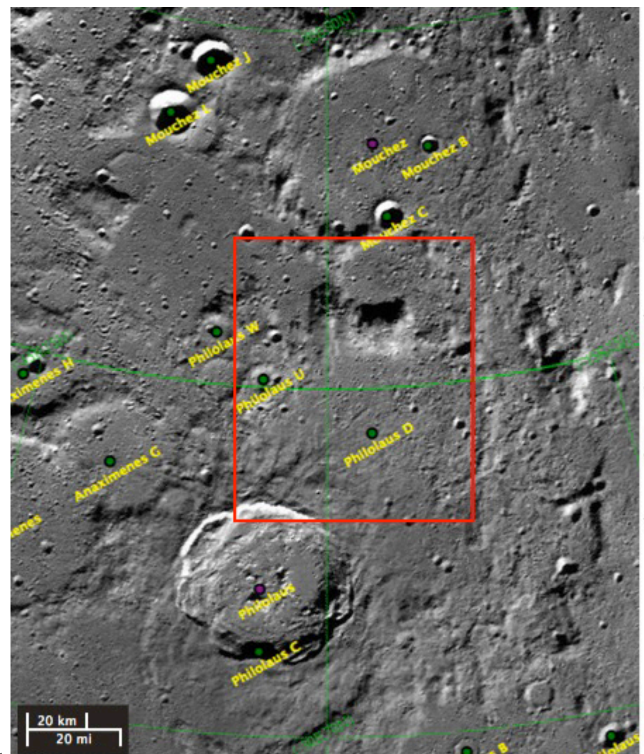
- Maneuver Terminology
  - LEC Phase: OCMs (Orbit Circularization Maneuvers)
  - Multiple Phases: ECMs (Eccentricity Correction Maneuvers)
  - Multiple Phases: OTMs (Orbit Trim Maneuvers)
  - Decommissioning Phase: BTD (Burn-to-Depletion)

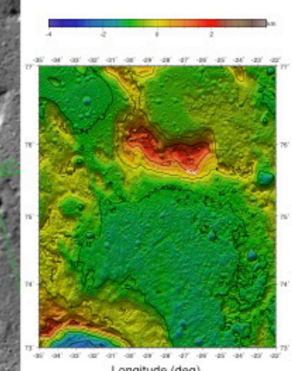
ECM-17 Design

- Maneuver Design Objectives
  - Do not disturb Lunar Heritage Sites (the only hard “requirement”)
  - Impact on the near side of the Moon (to be able to observe impact from Earth)
  - Impact in the northern hemisphere (to be able to see execution of BTD maneuvers)
  - Stay more than 2 km above lunar topography as long as possible
  - Design was finalized on November 13th, just over a month from impact !









Targeting the Burn-to-Depletion Maneuver

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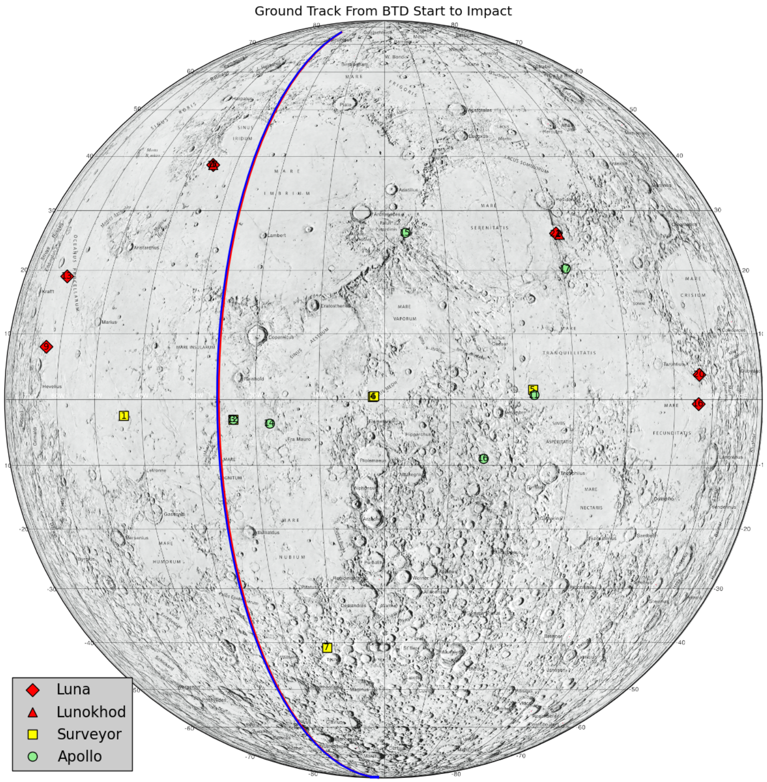

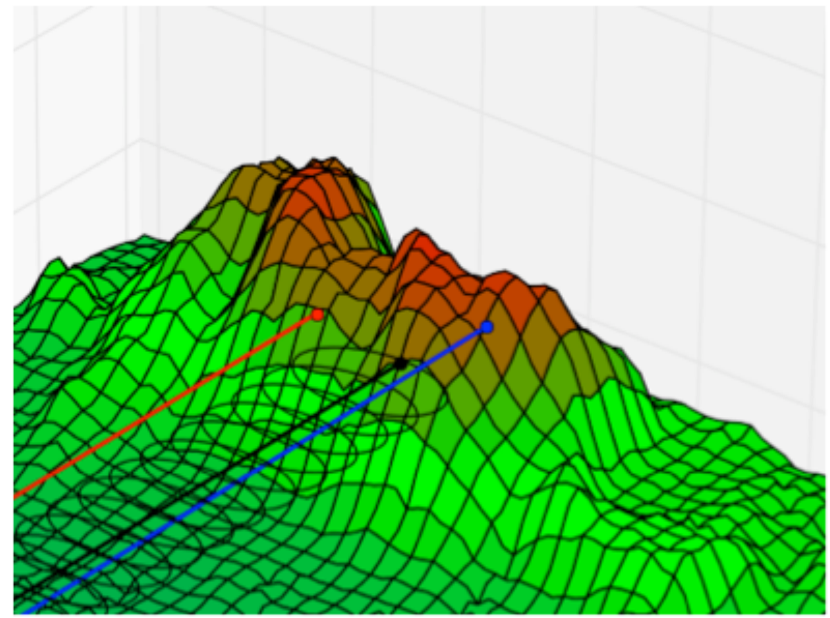

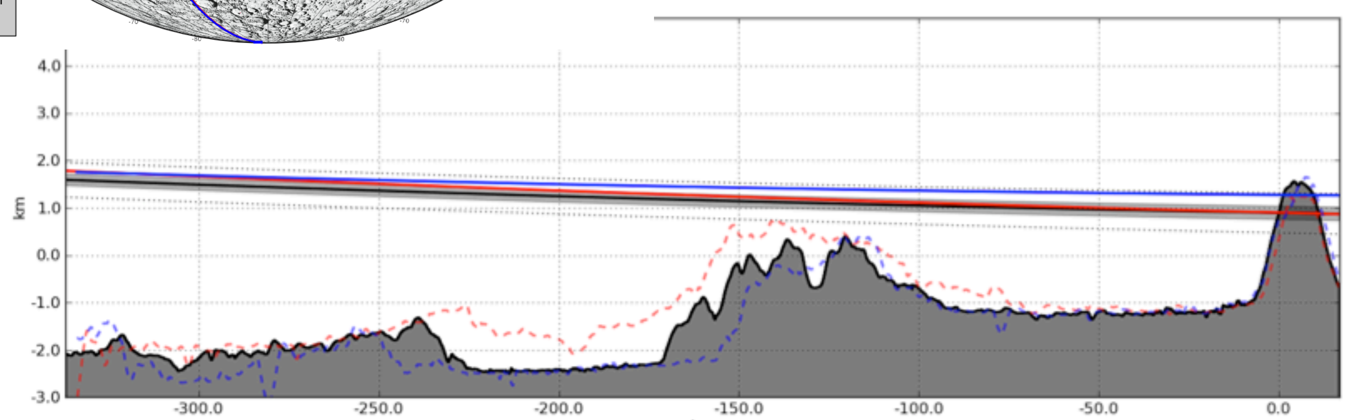

Comparison of pre- and post-BTD Trajectories

(10,000 sample BTD Monte Carlo)

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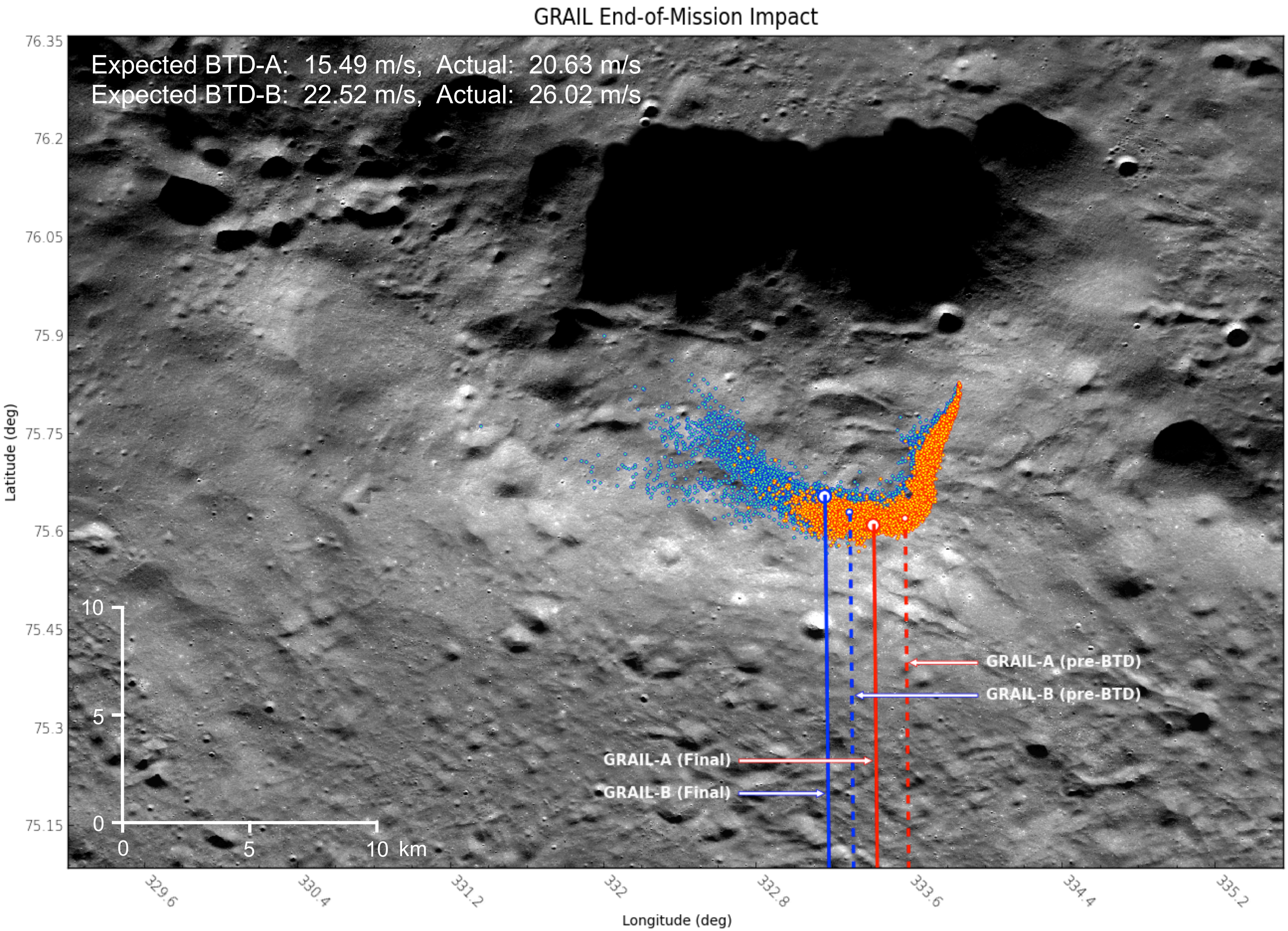

Snapshots from GRAIL Real-Time Display from BTD Maneuvers to Impact

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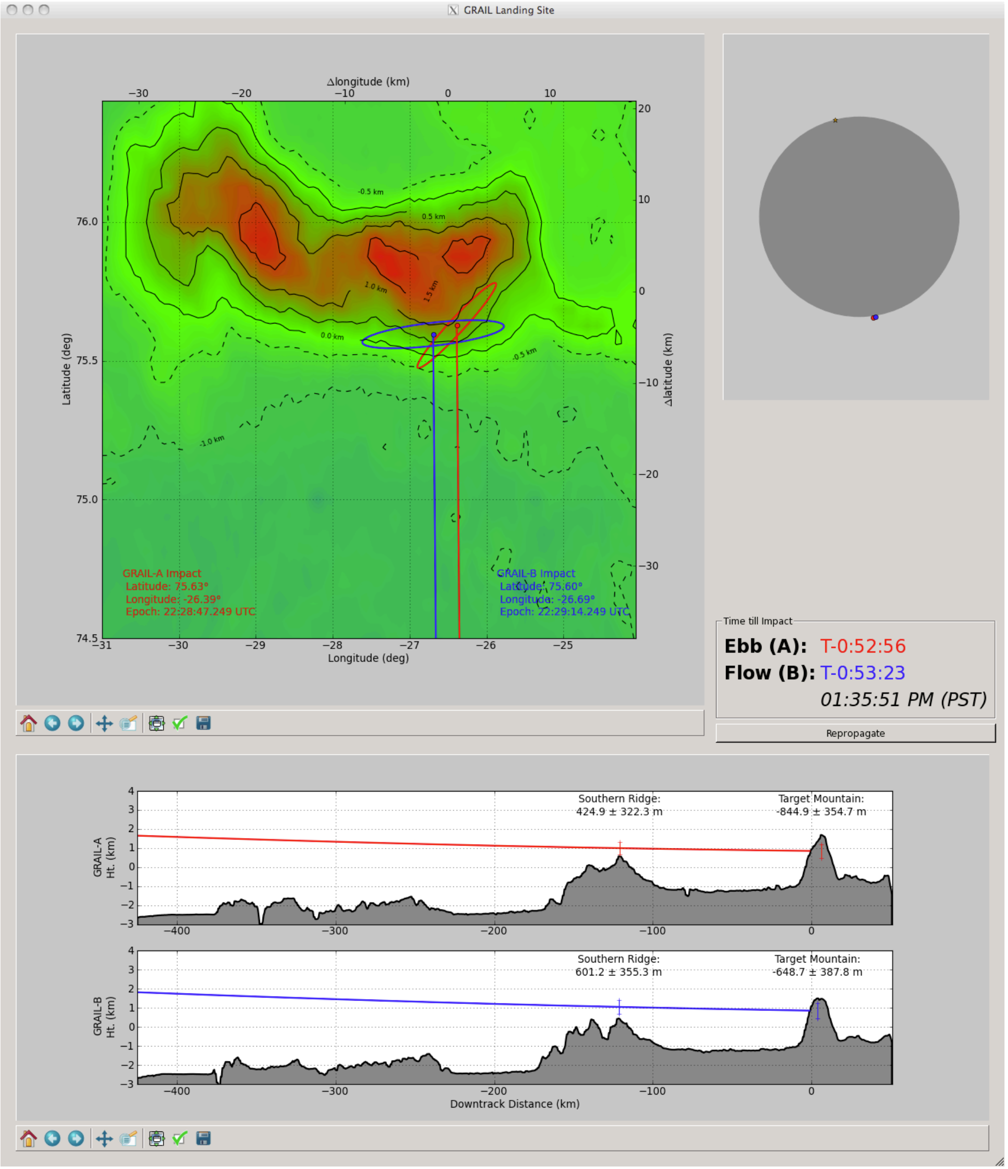

Final Orbits Prior to Impact

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- Animation from NASA/GSFC website: http://svs.gsfc.nasa.gov/vis/a000000/a004000/a004023/

GRAIL Impact Locations Imaged by LRO

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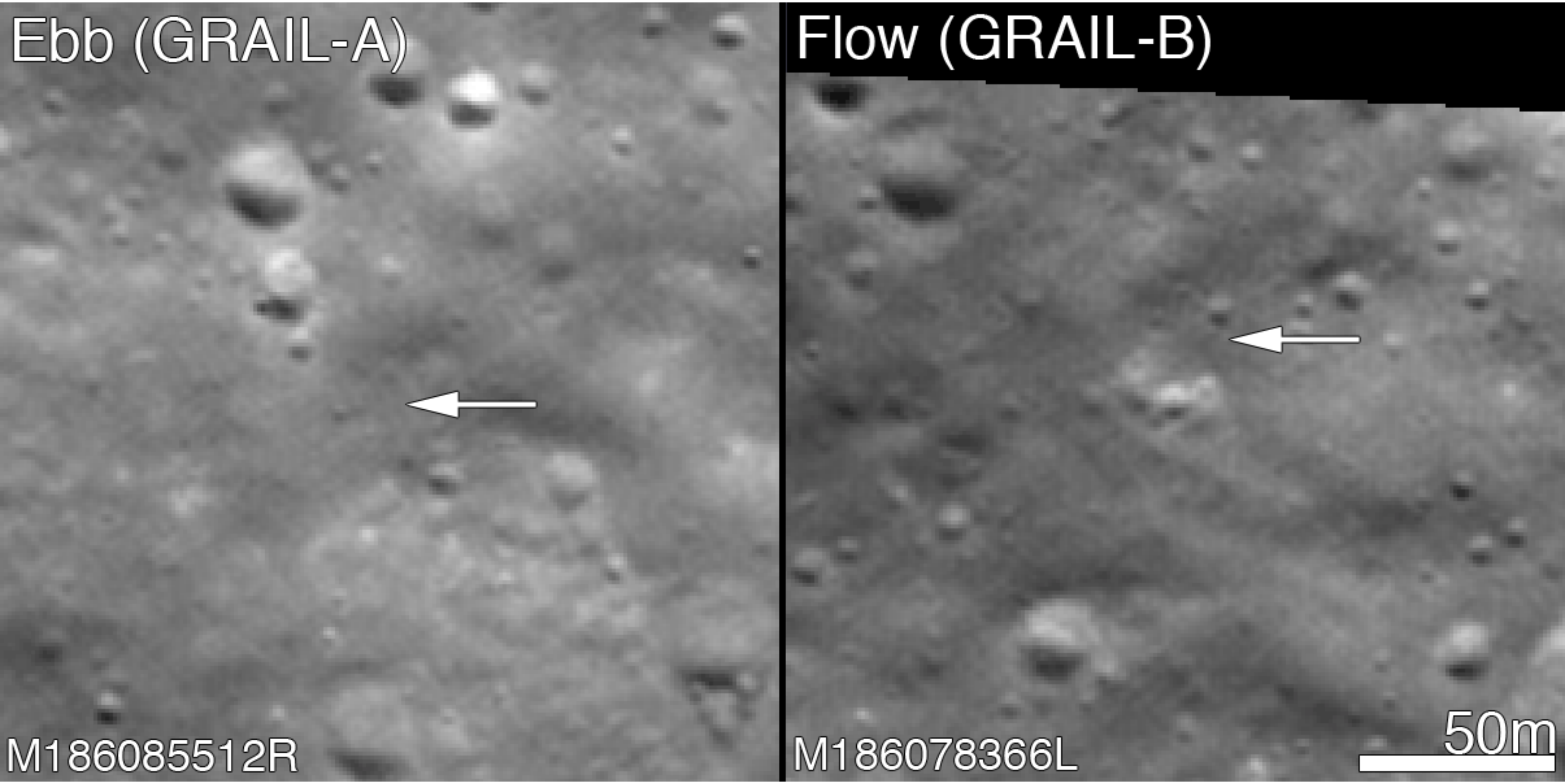

- Images from NASA/LRO website: http://www.nasa.gov/mission_pages/LRO/news/grail-results.html#.UwpHjSiFFpL

Mission and Navigation Operations

Trans-Lunar Cruise Phase Timeline

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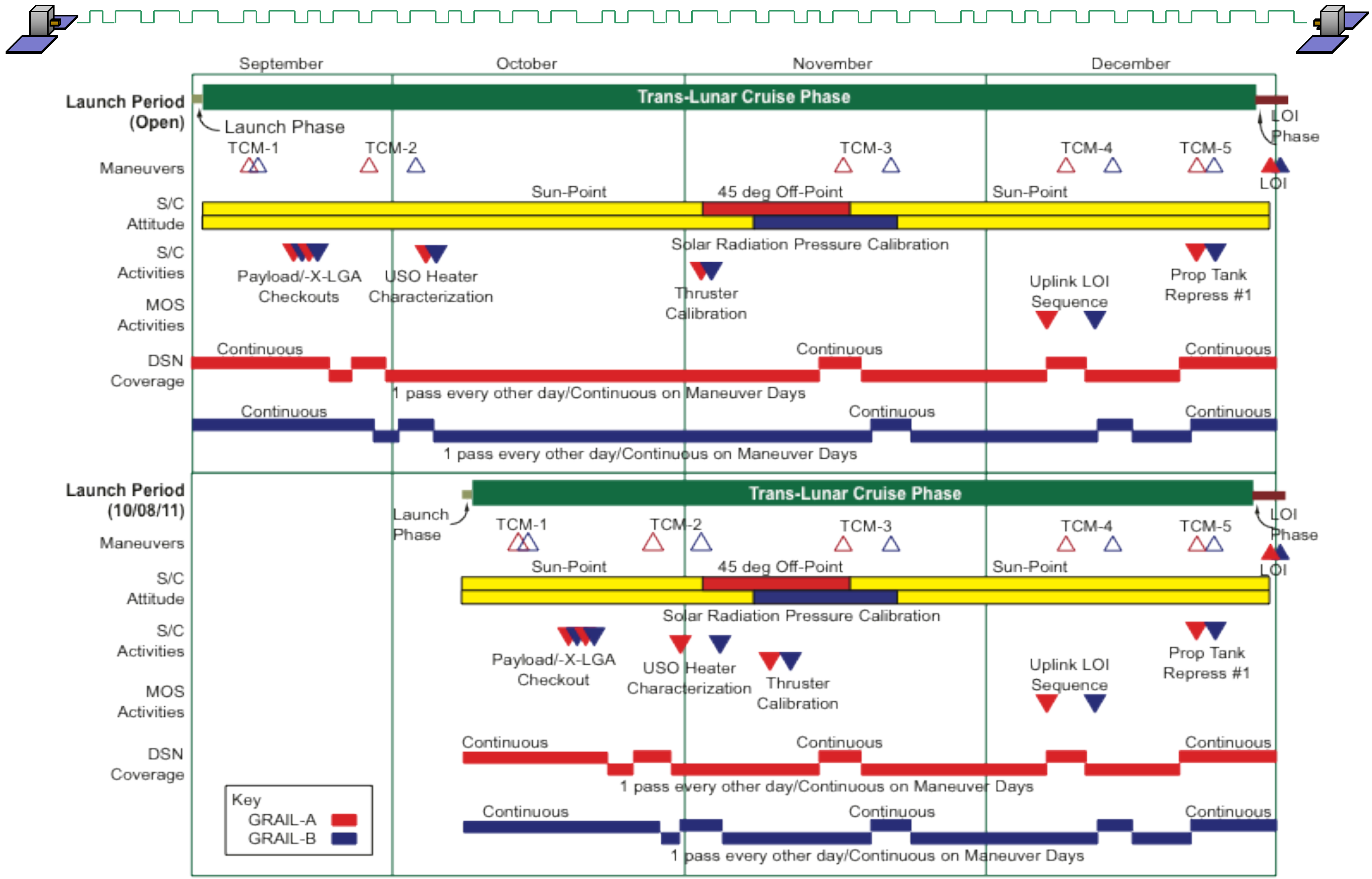
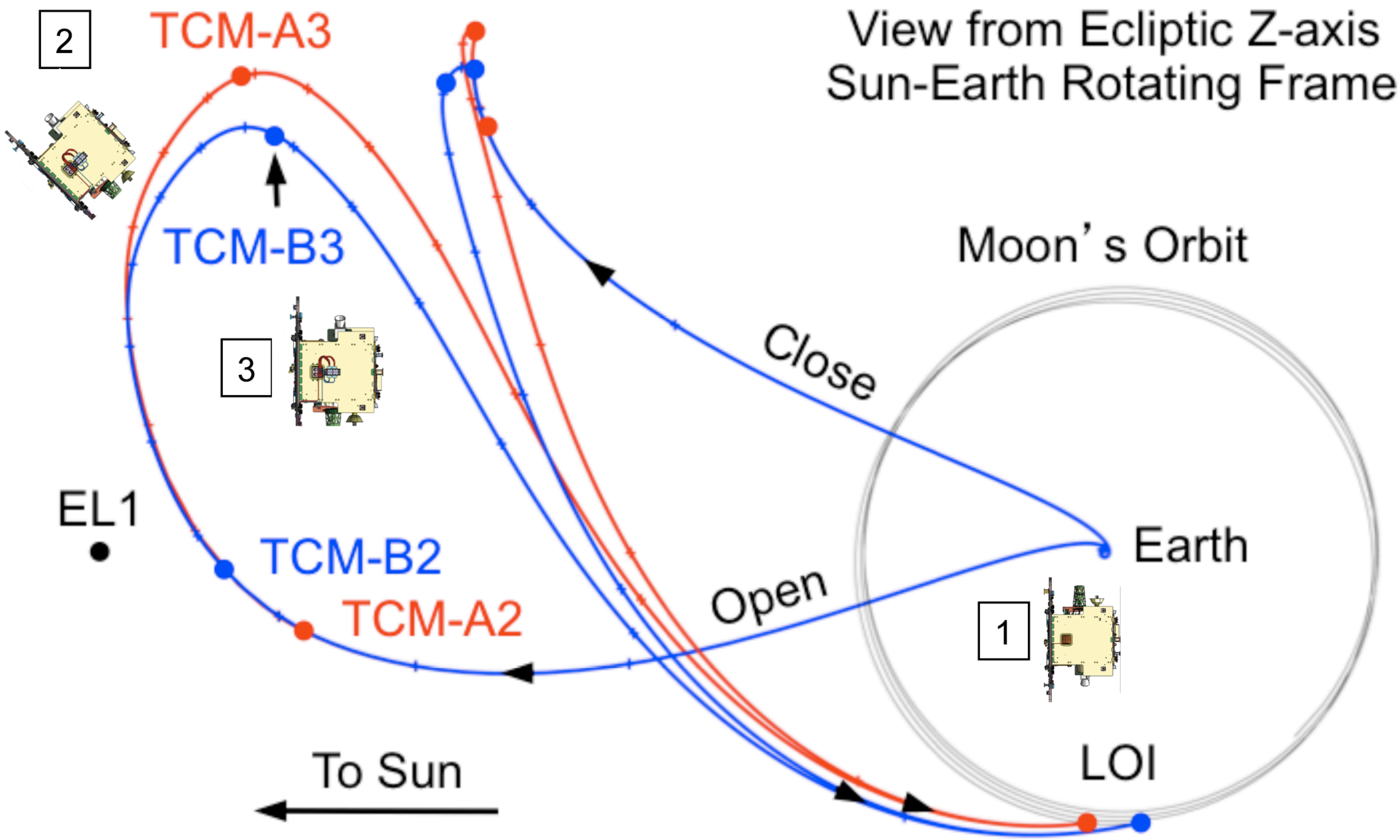


Spacecraft Attitude During TLC Phase



Maneuver Development Timeline in TLC Phase

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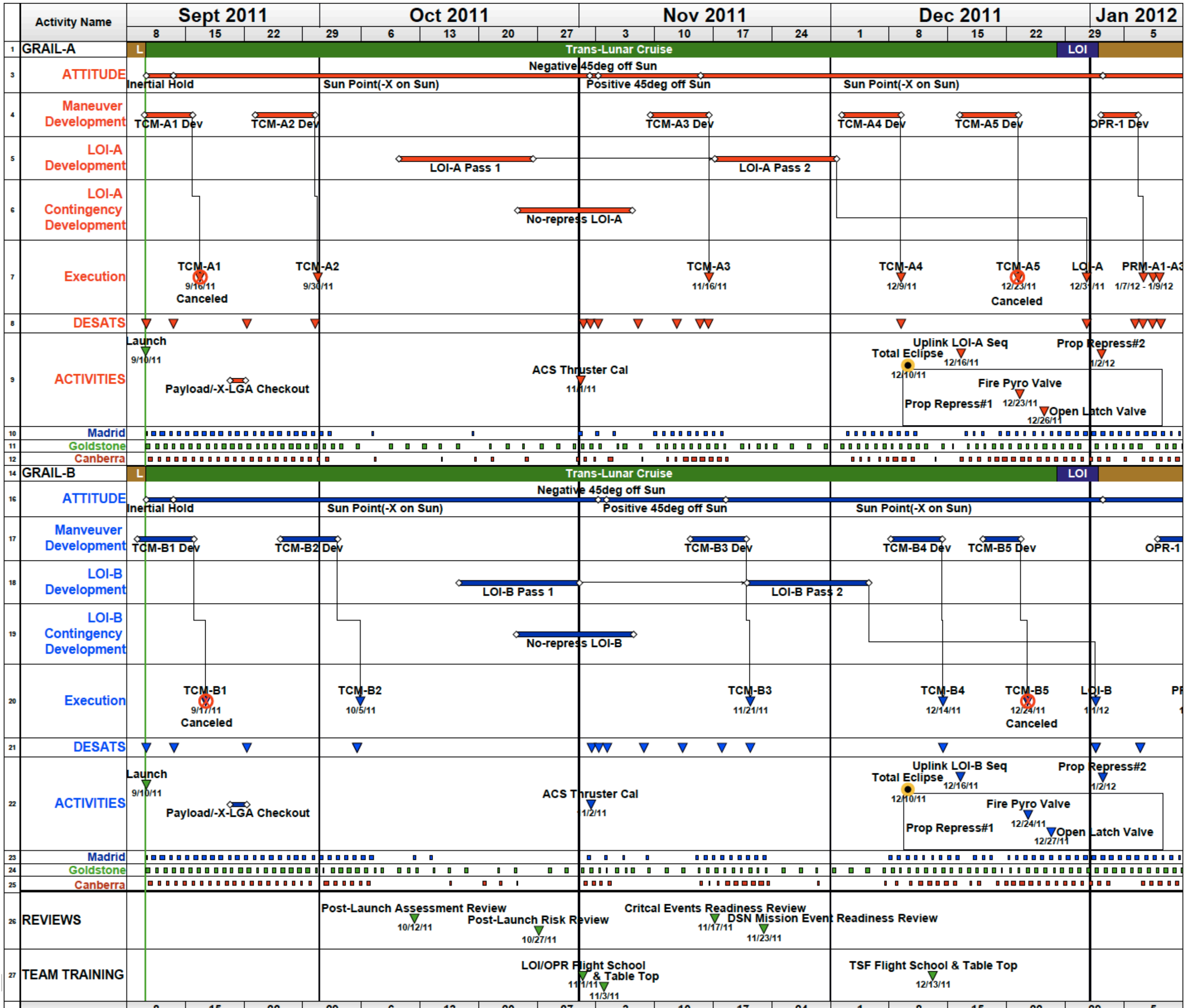
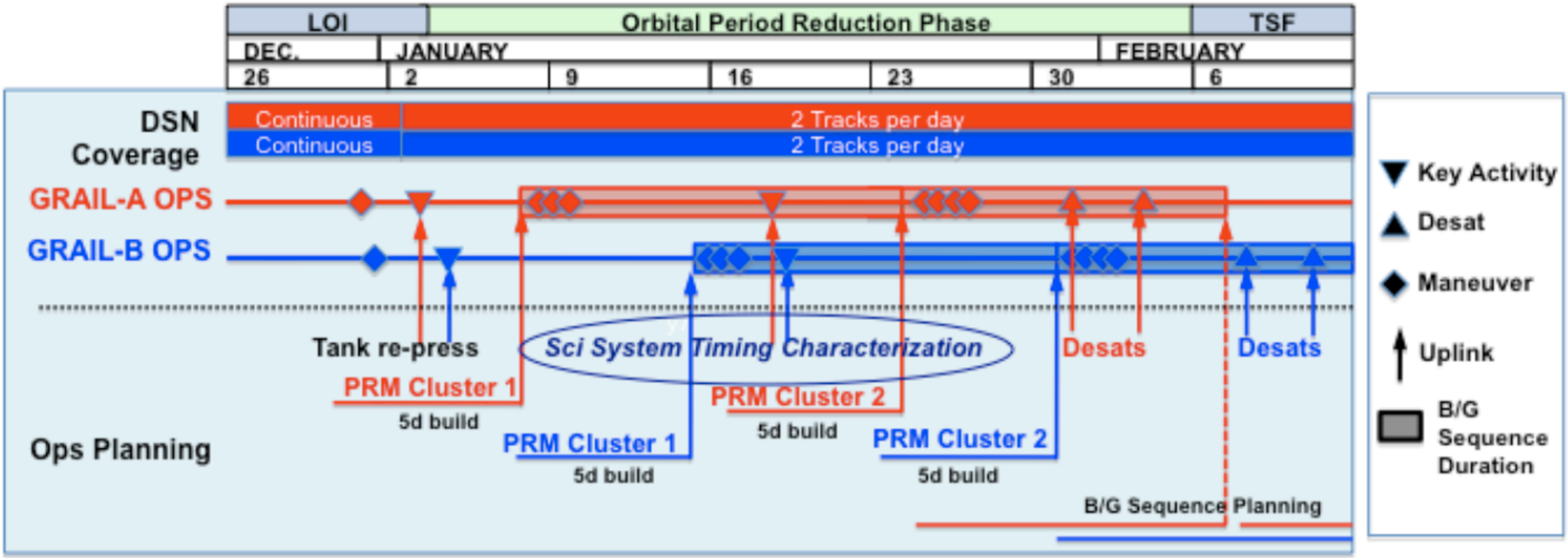
Discovery



Maneuver Development Timeline in OPR Phase

GRAIL
Discovery



- 7 Period Reduction Maneuvers (PRMs) per orbiter, divided into two clusters
- Reduced 11.5 hour orbit to less than 2 hours
- Utilized 5 day maneuver planning timeline
- Background (housekeeping) sequence merged with maneuver sequence

Orbit Determination Process

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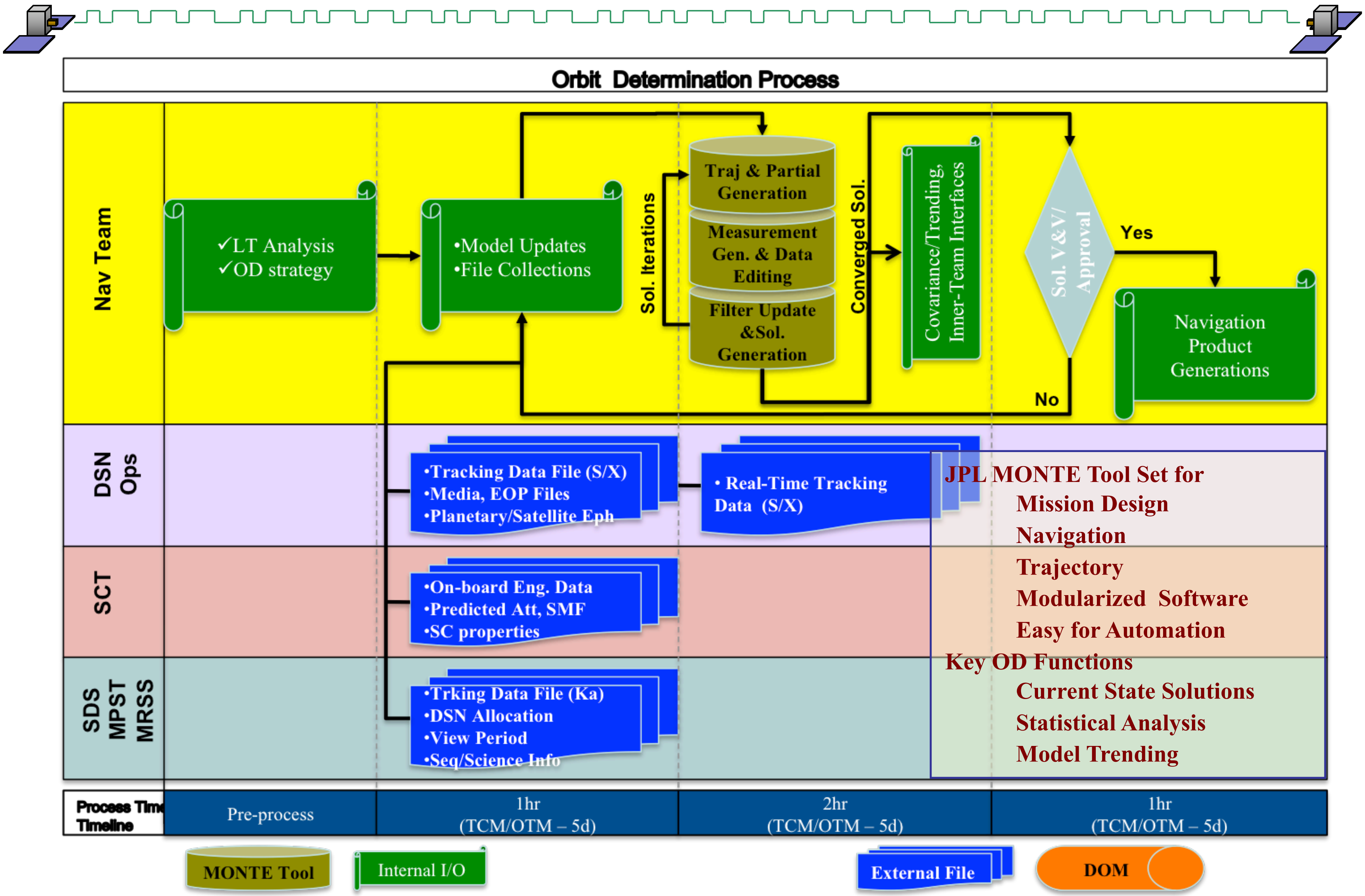

Orbit Determination Scenario in Lunar Orbit

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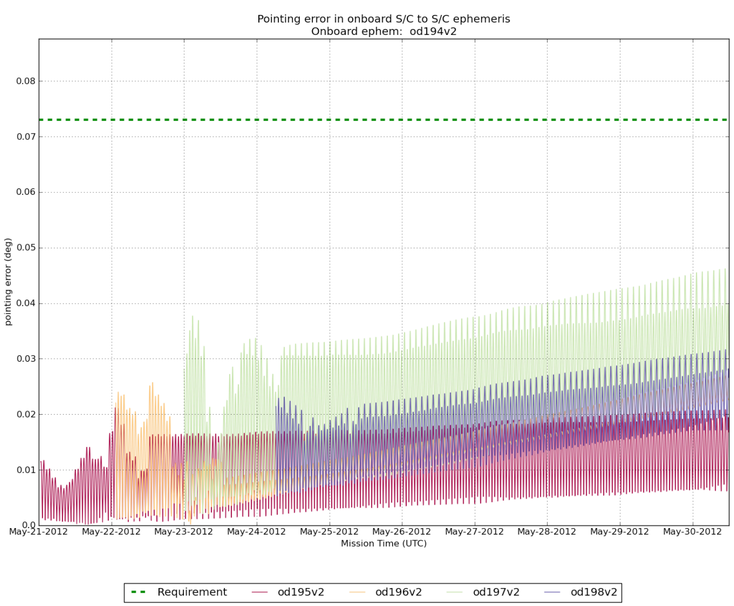
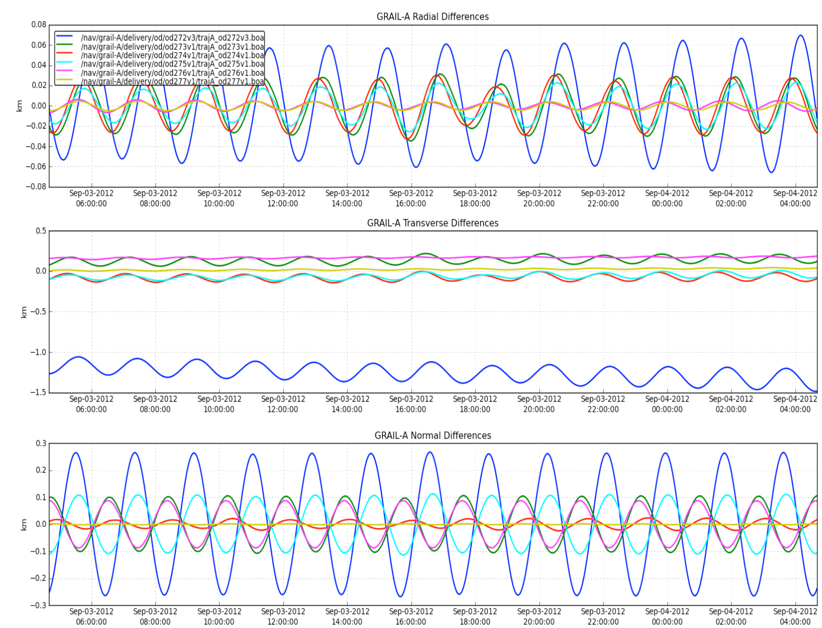
- Orbit determination frequency: 6-7 solutions per week
- Twice weekly delivery of predicted trajectories to project and DSN
- Monitor trajectory difference during solution overlap, long term trends in orbital elements, spacecraft-to-spacecraft pointing, predicted occultation entry/exit time, and predicted trajectory differences

Spacecraft-to-Spacecraft Pointing



Predicted Trajectory Comparison



Gravity Modeling

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- Initial gravity model – LP150Q spherical harmonic field
  - Derived from ground based S-band Doppler tracking of Lunar Prospector
- Subsequent models – developed by the GRAIL Science Team
  - Based on GRAIL LGRS Ka-band spacecraft-to-spacecraft range rate data
  - Global coverage
  - Various degree and order expansions and truncations

Date of First Use	Field ID	Truncation	Phase
March 7, 2012	lp150q	150x150	SCI
April 13, 2012	grail270a9a	200x200	SCI, LEC, LBA
June 7, 2012	grail360b6a	200x200	LBA
August 3, 2012	grail420c1a	200x200	LBA, TSF-XM, SCI-XM
September 1, 2012	grail420c1a	300x300	SCI-XM
October 26, 2012	grail540c3a	320x320	SCI-XM
December 6, 2012	grail660c5a	400x400	SCI-XM, DEC

Orbit Determination Activities in SCI-XM Phase

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Orbit Determination Activities in Blue	All Activities for Two Spacecraft Except for OTM Support (GRAIL-A Only)

MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
OD for Maneuver R/T Monitoring	OD for Maneuver R/T Monitoring	ECM Design Project Approval		Sequence Timing Update if Needed
Maneuver R/T Monitor Setup	Maneuver R/T Monitor Setup	Daily OD	Daily OD	Daily OD
ECM Maneuver R/T Monitoring Quick Assessment OD Reconstruction Product Delivery Weekend OD	**OTM Maneuver** R/T Monitoring Quick Assessment OD Reconstruction Product Delivery Weekend OD	Develop Staffing Plan, Tracking Data Delivery Schedule and OD Delivery Schedule for Next Week	ECM Covariance Analysis	
OTM Design	ECM Design			ECM R/T Monitoring Prep
Trajectory Prediction with/without OTM	ECM Design Navigation Internal Approval	ECM Design Validation	Trajectory Prediction with/without ECM	
OTM R/T Monitoring Prep				

Note: Activity Durations Approximate

Contingency Planning during the TLC Phase

TCM Planning

- Backup TCM Opportunities
  - Backup opportunities existed for all TCMs (on both GRAIL-A and GRAIL-B)
  - TCM-1: Backup scheduled (at least) 4 days after nominal
  - TCMs 2, 3, and 4: Backups scheduled one week after nominal TCM
  - TCM-5: Backup scheduled at LOI-3 days (nominal at LOI-8 days)

- Accommodating Launch Delays
  - TCM-1 and TCM-2 occur at a fixed time relative to launch
  - TCMs 3, 4, and 5 occur at a fixed time relative to LOI
  - TCMs 2 and 3 combined for launch dates “late” in the launch period due to shrinking TLC Phase timeline

Maneuver Development Timeline in TLC Phase

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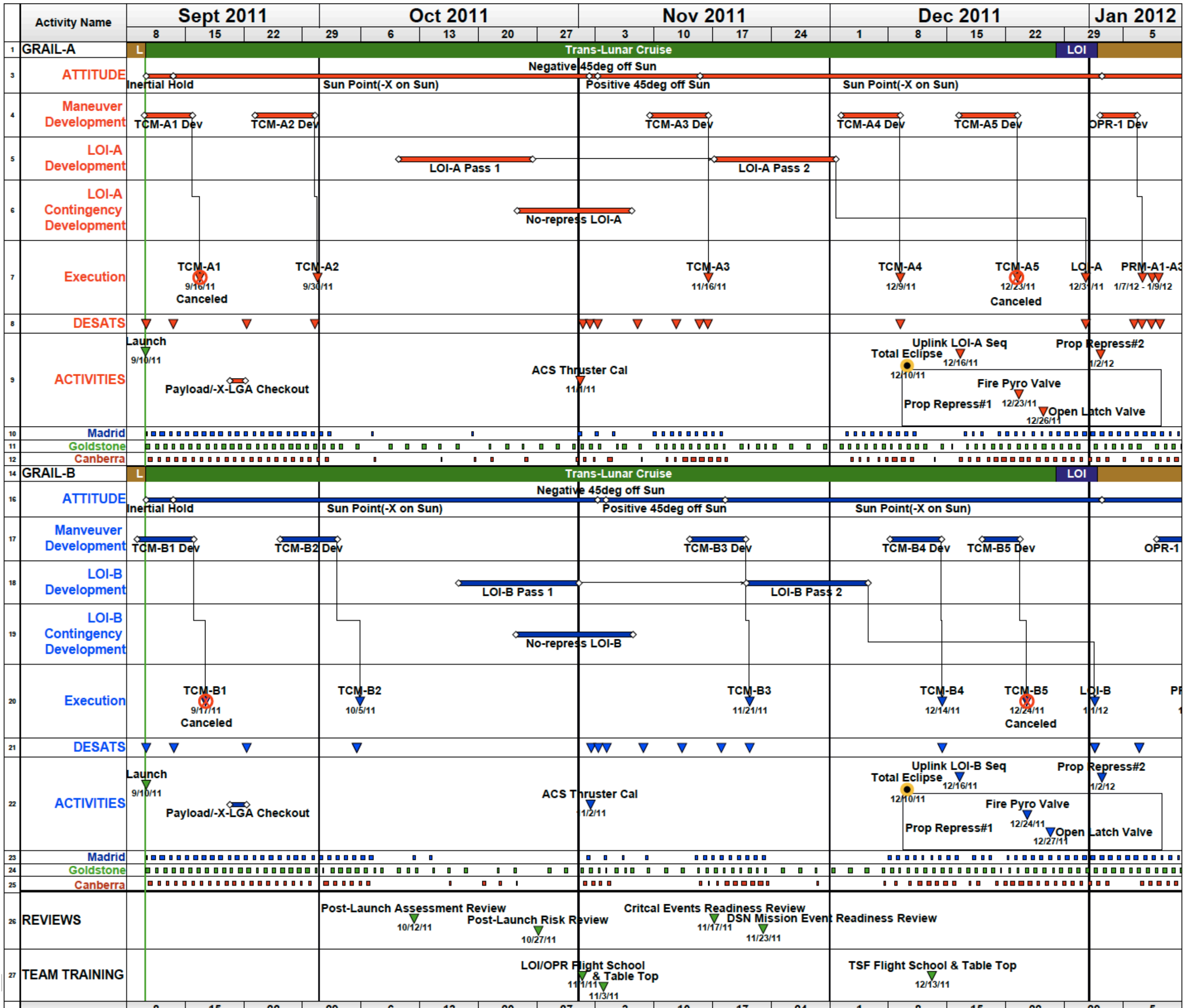
Discovery



TCM-5 Planning

- To ensure that all the science requirements can be satisfied with TCM-5, must show $\pm 3\sigma$ TCM-5 values can be handled adequately
- To be able to cancel TCM-5, must show $\pm 3\sigma$ TCM-4 dispersions can be handled adequately — or, if some $\pm 3\sigma$ TCM-4 dispersions are too large, must establish some boundaries on those parameters
- Targeted LOI Parameters
  - SMA (semi-major axis), RCA (radius of closest approach), INC (inclination), LAN (longitude of the ascending node), AOP (argument of periapsis), TTP (time to periapsis)
  - The most critical delivery parameters were TTP and RCA
- Derived Requirements
  - Ensure no orbital crossing (i.e. COLA (collision avoidance) ≥ 10 km) while placing GRAIL-A and GRAIL-B into the science formation
  - LOI Phase: LOIs capture spacecraft into 11.5 hour orbits
  - OPR Phase: Two clusters of PRMs reduce periods to near science periods
  - TSF Phase: Max ΔV of each of the TSMs derived such that the execution error propagation does not exceed the expected limit for the formation

TCM-5 Go/No-Go Criteria

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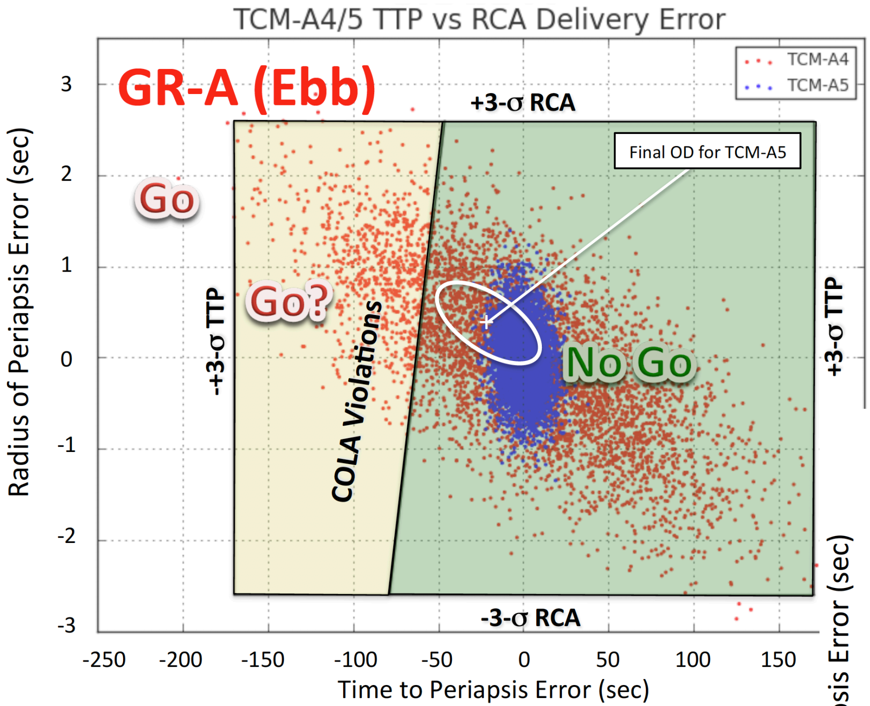
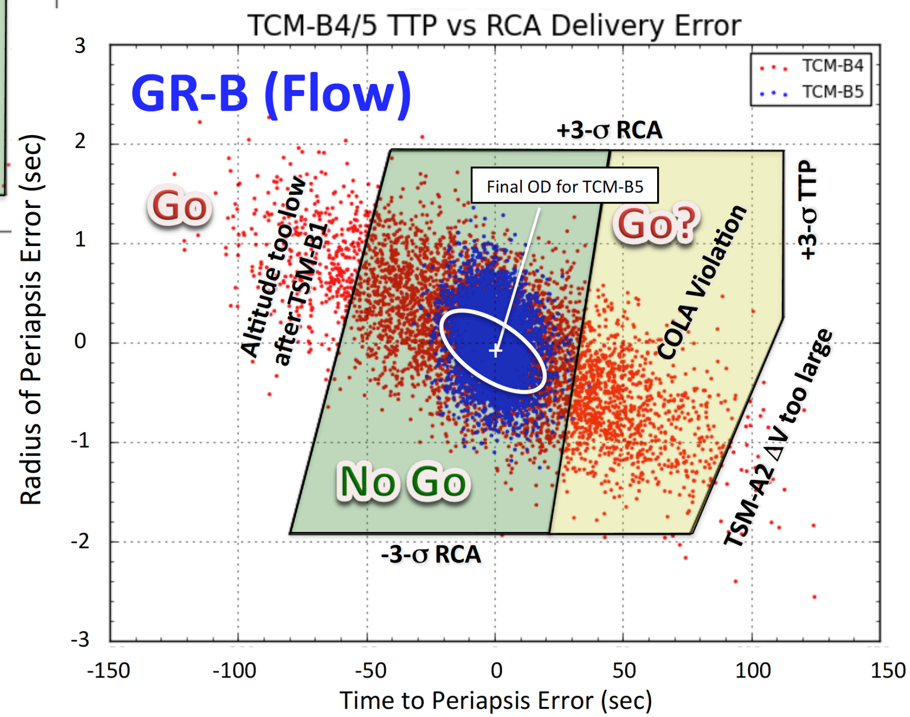


TCM-A5 canceled
TCM-B5 canceled



Backup Slides

- GRAIL References
- Trans-Lunar Cruise Trajectory Characteristics
- Maneuver Strategy for the Transition to Science Formation Phase
  - Establishing an Orbit Formation While Accommodating Maneuver Execution Errors

References

(the author list of the References is composed of the members of the GRAIL MDNAV Teams)

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  - Roncoli, R. B., Fujii, K. K., "Mission Design Overview for the Gravity Recovery and Interior Laboratory (GRAIL) Mission", *AIAA/AAS Astrodynamics Specialist Conference*, AIAA 2010-8383, Toronto, Ontario, Canada, August 2010.
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  - You, T., Antreasian, P., Broschart, S., Criddle, K., Higa, E., Jefferson, D., Lau, E., Mohan, S., Ryne, M., Keck M., "Gravity Recovery and Interior Laboratory Mission (GRAIL) Orbit Determination", *23rd International Symposium on Space Flight Dynamics (ISSFD)*, Pasadena, California, November 2012.
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TLC Trajectory Design

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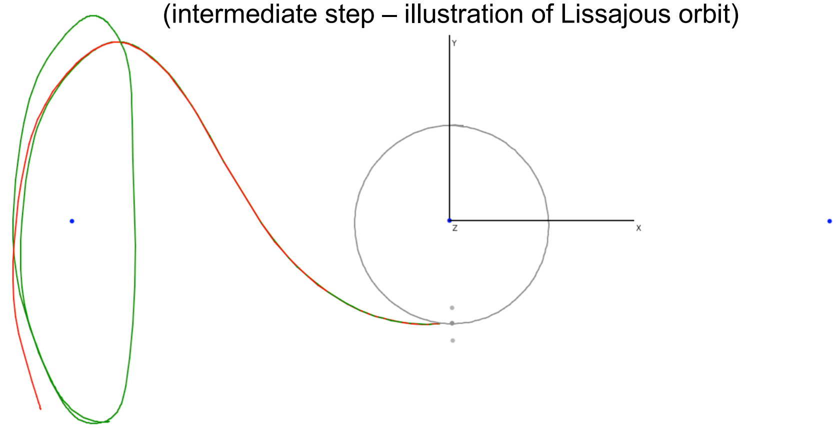
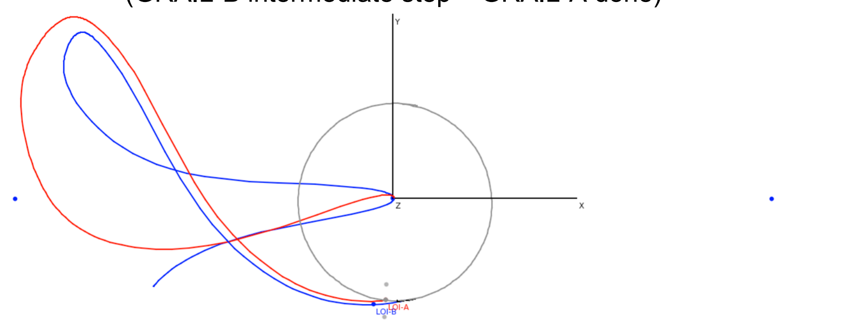
[Snapshots of the Trajectory Design Process Illustrated in the Video Clip presented earlier]

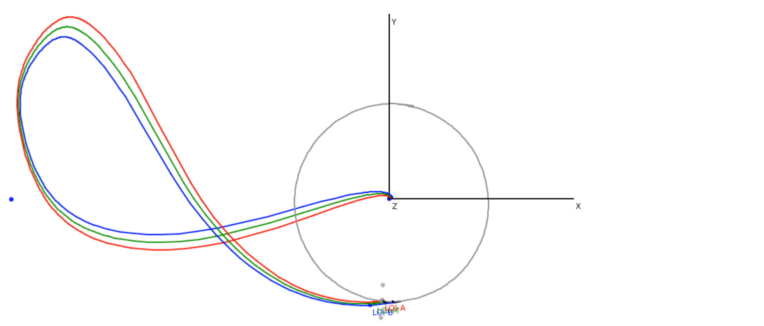
Backwards propagation of GRAIL-A trajectory from the Moon
(intermediate step – illustration of Lissajous orbit)



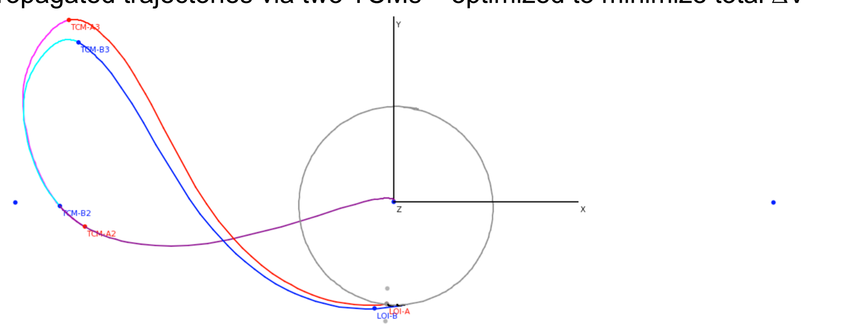
Backwards propagation of GRAIL-B trajectory from the Moon
(GRAIL-B intermediate step – GRAIL-A done)



Backwards propagation of “common” (middle) trajectory from the Moon



Final converged common launch trajectory inserted into backwards propagated trajectories via two TCMs – optimized to minimize total ΔV



Visualization of TLC Trajectory

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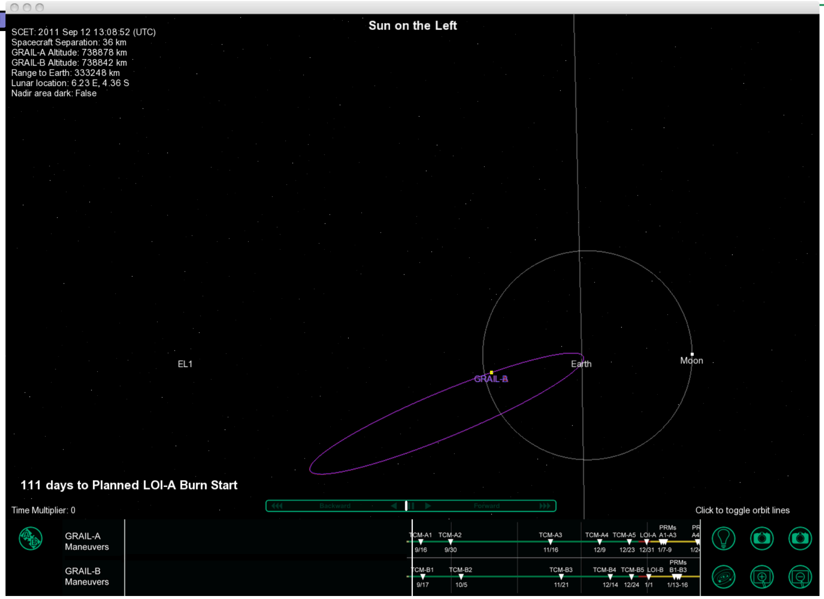
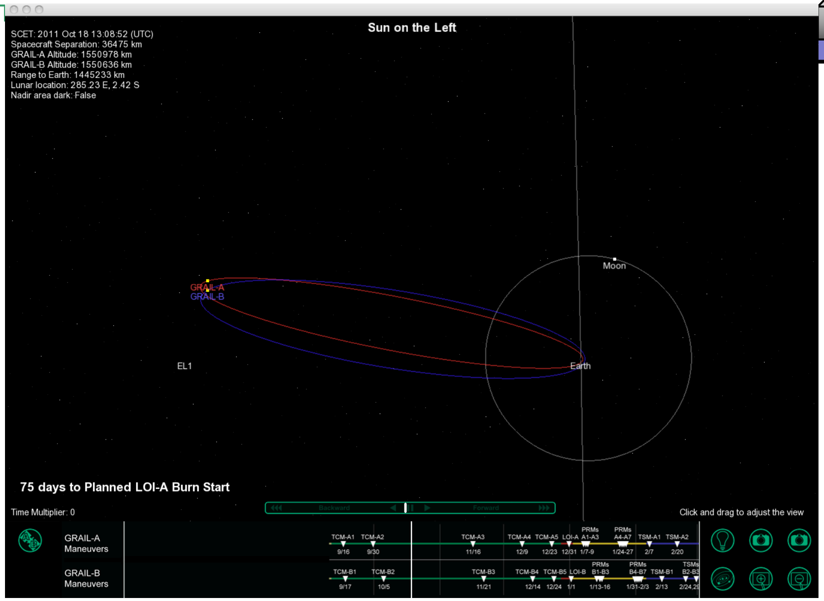
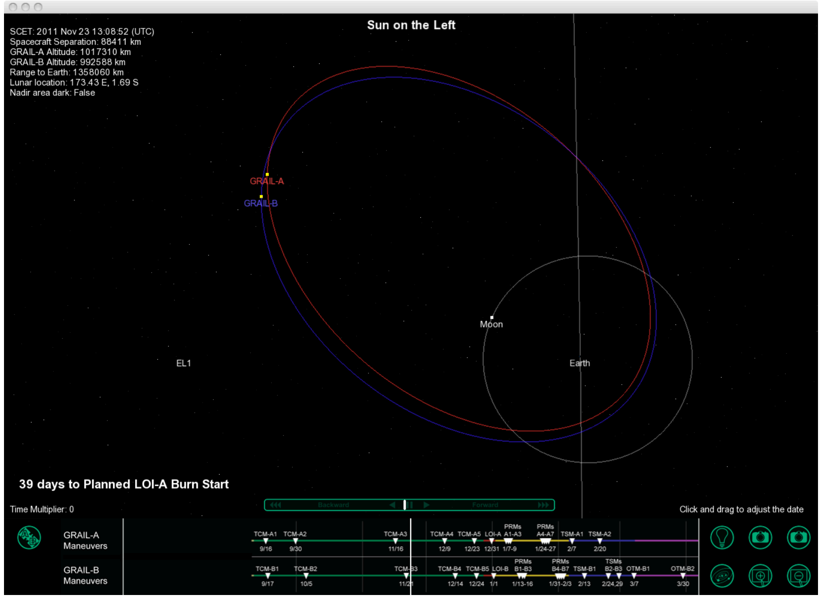
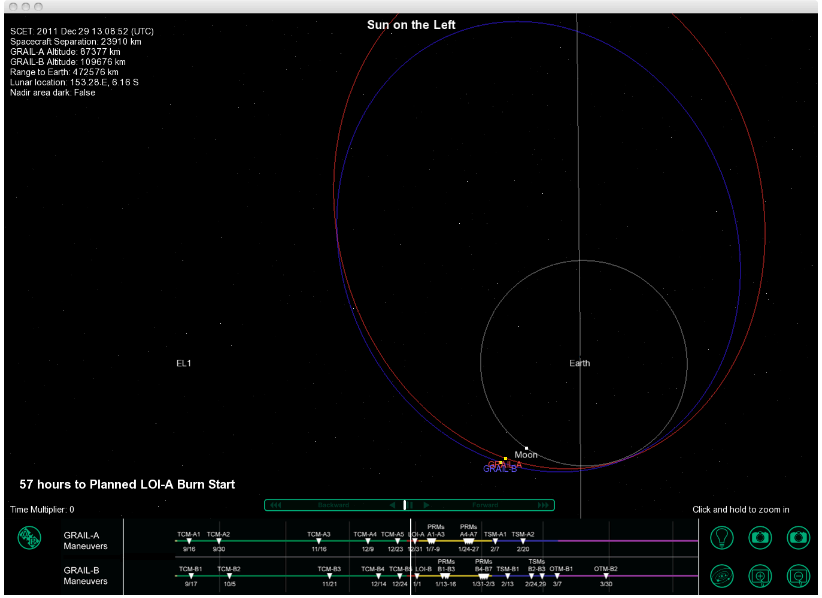
[Snapshots of the Change in Two-Body Ellipse Illustrated in the Video Clip presented earlier]









Trans-Lunar Cruise “Two-Body Energies”

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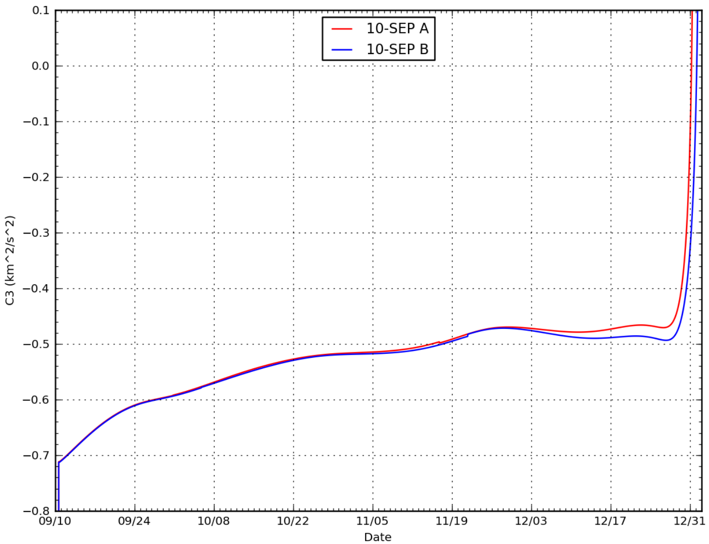
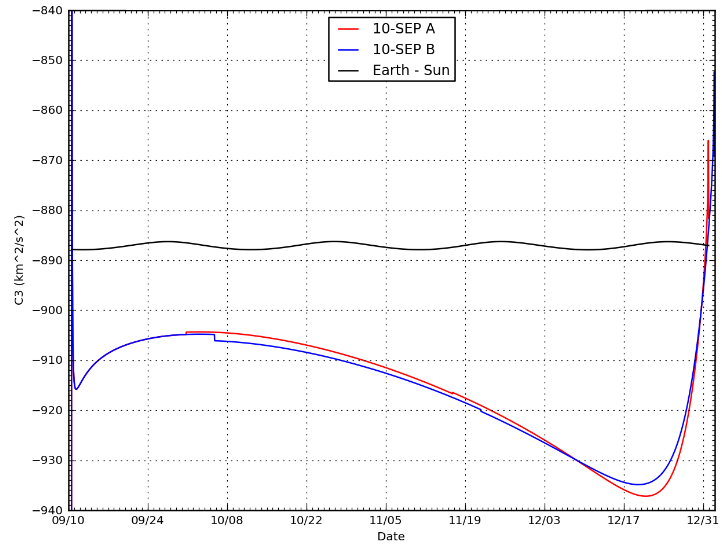
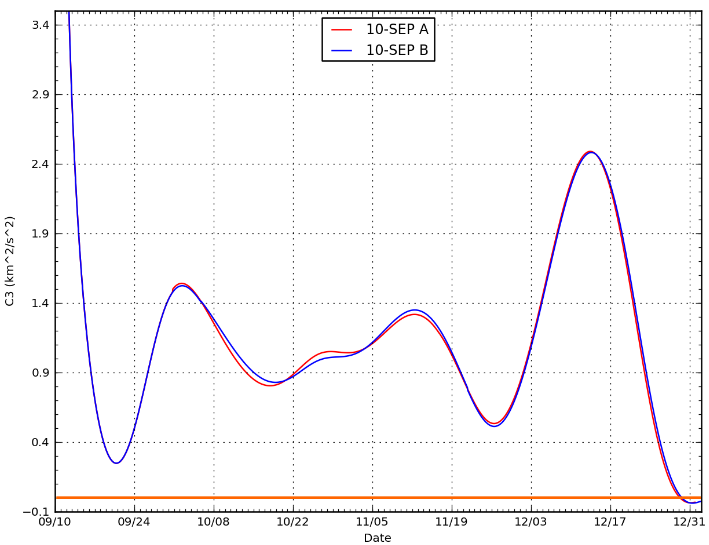
GRAIL C_3 with respect to the Earth



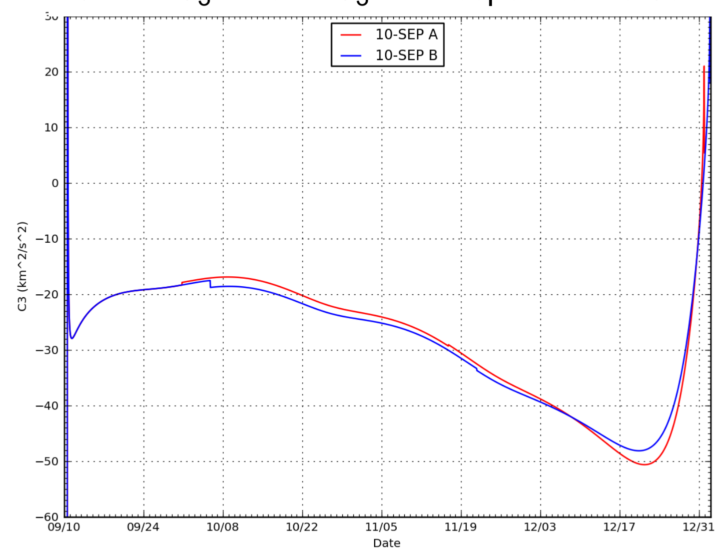
GRAIL C_3 with respect to the Sun



GRAIL C_3 with respect to the Moon



GRAIL C_3 – Earth C_3 with respect to the Sun



$C_{3\text{-Moon}} < 0$ at LOI

Transition to Science Formation Phase

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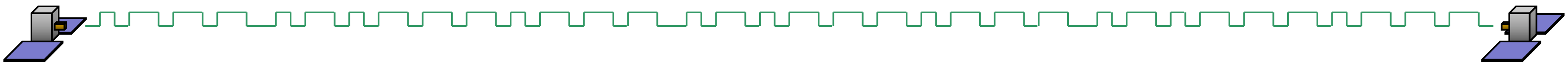
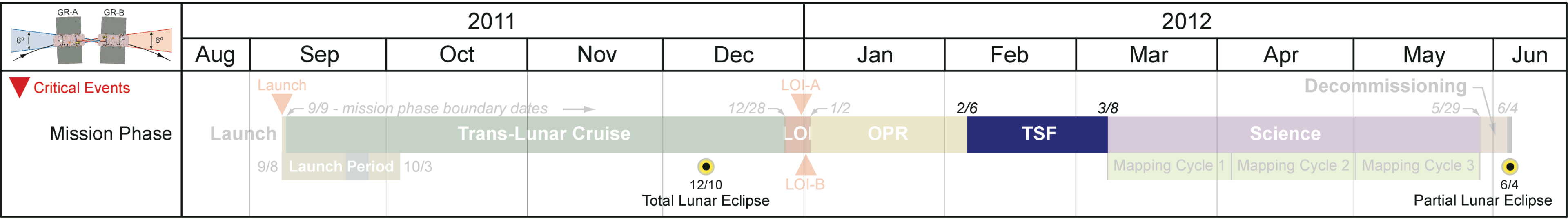
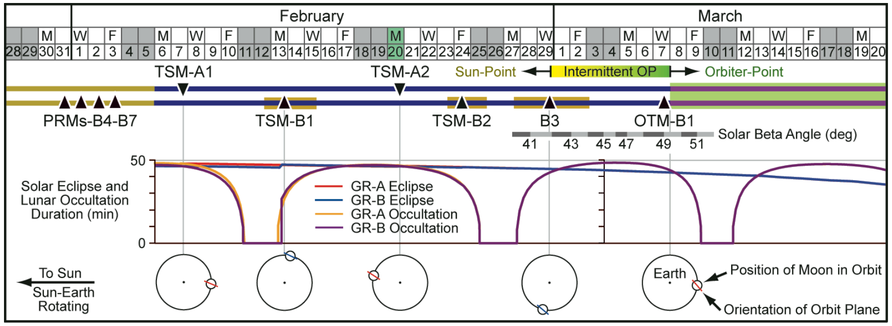




- Objective of the TSF Phase
  - To maneuver the two GRAIL orbiters from randomly phased initial conditions into a coordinated formation in the desired science orbit
  - To test and calibrate the payload prior to the start of the Science Phase
- Key Design Features
  - Until this point in the mission, the orbiters had been independently operated – essentially flying two separate missions
  - Five deterministic maneuvers were used to establish the proper formation at the start of the Science Phase
  - The TSF strategy was designed to
    - Avoid a collision by controlling the phasing of the two orbiters
    - Accommodate variations caused by maneuver execution errors



TSF Phase Maneuver Strategy

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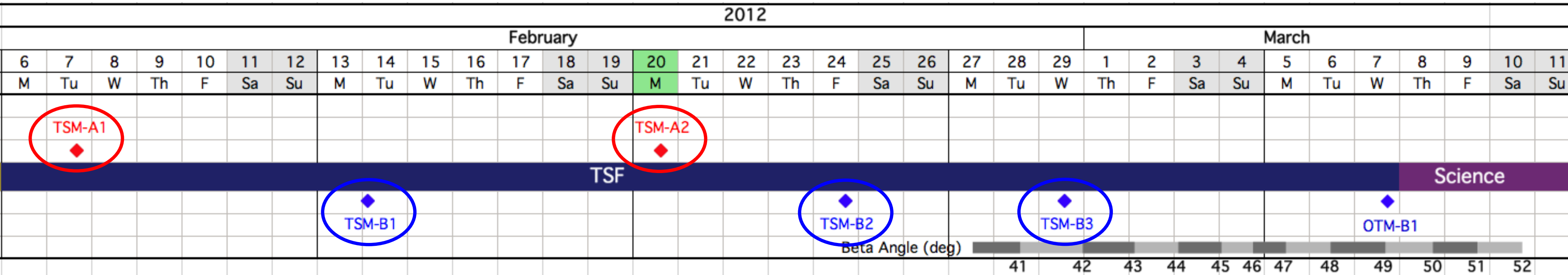

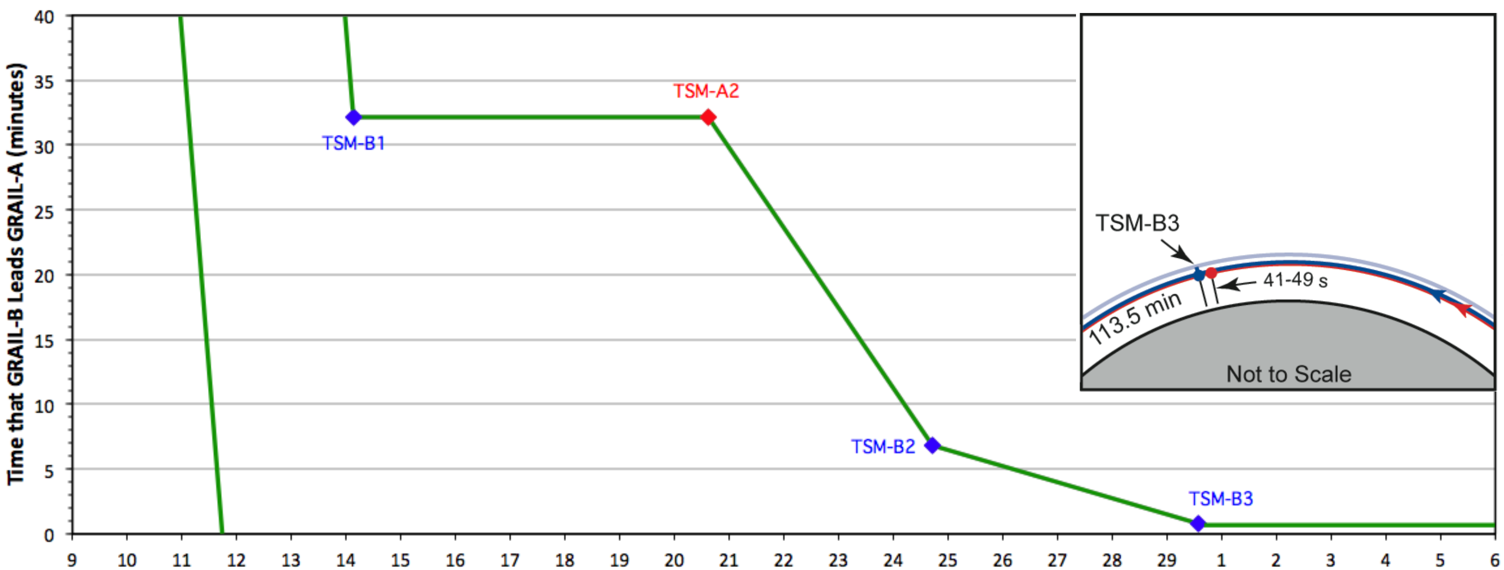

Impact of Execution Errors on Maneuver Timing

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